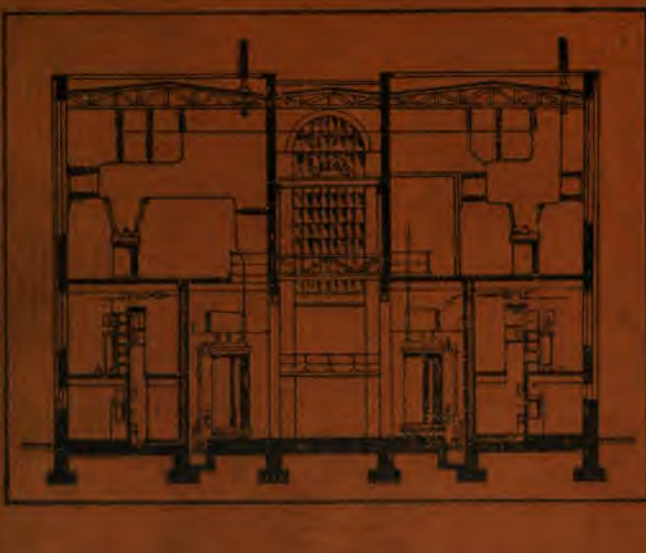
Electric Power Systems



TAYLOR

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ELECTRIC POWER SYSTEMS

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ELECTRIC POWER SYSTEMS

A PRACTICAL TREATMENT OF THE MAIN CONDITIONS, PROBLEMS, FACTS AND PRINCIPLES IN THE INSTALLATION AND OPERATION OF MODERN ELECTRIC POWER SYSTEMS

FOR SYSTEM OPERATORS, GENERAL ELECTRICAL ENGINEERS AND STUDENTS

BY

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PREFACE

THE subject *Electric Power Systems* is so very broad that it might appear presumptuous to attempt to deal with it in a volume of this size. Anything like an exhaustive treatment of the various branches of electric power system installation and operation is, of course, impossible within the present limitations of space. Nevertheless, the author believes that the information here presented will be of practical value to the operators in all departments of electricity undertakings, to general electrical engineers interested in the efficient production and distribution of electrical energy, and to students.

The subject matter is that which the author's experience with electric power systems in many parts of the world leads him to think will be most useful to the reader who desires an introductory treatment of the technical facts and principles governing modern practice in the larger electric power systems, as well as a review of the said practice.

General circuit conditions are considered, the most important methods and problems in generation, transmission and distribution practice are explained, and special attention is paid to system operation, to the various "system factors" used in practice, and to the importance of keeping reliable operating records.

Little information has hitherto been published in convenient form concerning many of the points discussed herein. For this reason, and because the information given is based on actual experience, the author trusts that this volume will be helpful to all those interested in the basic problem of electricity supply.

WM. T. TAYLOR.

LONDON.

ERRATA

Page 14, *line* 7. *For* $1/\sqrt{3}$ *read* $\dot{i}/\sqrt{3}$.

Page 14, *line* 8. *For* 1^2R *read* I^2R.

Page 23, *3rd line from bottom*—

For $\eta = \dfrac{E_r\ I \cos\varphi}{E_r I \cos\varphi + I^2R}$

read $\eta = \dfrac{\sqrt{3}E_r\ I \cos\varphi}{\sqrt{3}E_r I \cos\varphi + 3I^2R}$; where E_r = voltage between line and neutral at the receiving end; and the other symbols have the same meanings as before. The power loss in the line as a percentage of the power transmitted is: $100 \times 3 \times I^2R/\sqrt{3}\ EI \cos\varphi) = 173{\cdot}2\ IR/E \cos\varphi$.

Page 24, 1*st line*. *For* adding arithmetically *read* adding vectorially.

Page 24, *lines* 10 *and* 13. *For* 2 *read* 200.

Page 24, *lines* 11 *and* 14. *For* $\sqrt{3}$ *read* 173·2.

Page 24, *lines* 15-17 *should read*: "The percentage regulation (volts drop) is therefore: For a single-phase line 200 IZ/E; and for a three-phase line 173·2 IZ/E; where $IZ = \sqrt{[(IR)^2 + (IX)^2]}$.

Page 26, *3rd line from bottom*. *For* $I\sqrt{3}$ *read* $1/\sqrt{3}$.

Page 29, *line* 25. *For* $kW \times D \times N$ *read* $kW \times l \times N$.

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SYMBOLS AND ABBREVIATIONS

Except where otherwise stated, the following symbols and abbreviations, adopted by the International Electrotechnical Commission, are used in this volume—

P	= power	X	= reactance
η	= efficiency	Z	= impedance
f	= frequency	A	= ampere
φ	= phase displacement	V	= volt
E	= electromotive force	μF	= microfarad
I	= current	kW	= kilowatt
R	= resistance	kVA	= kilovolt-ampere
C	= capacity	kWh	= kilowatt-hour
L	= self-inductance		

ELECTRIC POWER SYSTEMS

CHAPTER I

INTRODUCTION

MECHANICAL power, transformed in the electric generator, produces what may aptly be termed the highest known form of power, because electric power can be changed with unequalled directness and simplicity into such forms as motive power, light, heat, and chemical action. The conversion of mechanical energy into electrical, or *vice versa*, has been brought to such a pitch of development that the losses in the conversion do not exceed 10 per cent, at the most. Present day electric generator efficiency is above 97 per cent ; the efficiency of large power transformers is over 99 per cent ; the conversion of energy in the rotary-converter is around 98 per cent ; and the efficiency of the electric motor is about 97 per cent.

During recent years, enormous strides have been made in improved methods of power generation and transmission. The steam-turbine and steam generating equipment have made, perhaps, the most marked progress. The largest developments of the present day in the field of electrical engineering indicate phenomenal progress ; for instance, we have—

PRESENT-DAY MAXIMUM UNIT CAPACITY.

Steam-turbo generator	60,000 kVA
Hydro-electric generator	37,000 kVA
Power transformer	60,000 kVA
Power transmission line	200,000 V
Underground cables	60,000 V

Efficiency. These developments mean still higher efficiencies. From the economic standpoint, the object of the operating engineer is to attain a series of better and still better efficiencies commencing at the coal dump and going all the way to and including the consumers' plant. Work towards this end is not restricted to new plant, but includes also efforts to improve the efficiency and general economy of boilers and steam units already in operation, wherein coal consumption can be greatly reduced. Such increases in efficiency, together with improvements in boiler and furnace construction, in electrical machinery and apparatus, and in methods of operation, all mean that a greater output can be obtained from a given size of plant. In hydro-electrics there is a still greater scope for obtaining higher efficiencies, commencing at the watershed itself. When water power is not available, the cost of fuel for power generation is invariably the factor of greatest importance, no matter how high the efficiency. The cost of fuel may be greater than 75 per cent of the total operating costs. With decreasing load factor, the relative magnitude of the fuel cost increases, due to increased steam consumption per kilowatt-hour produced, and there is also a proportional increase in auxiliary power at such fractional loads, so that general plant losses are all proportionally greater, the less the load factor. Increase in the diversity of electric service has resulted in improved load factor, thus making it possible to deliver a much greater total output with a given peak-capacity. Increased efficiency is due partly to the installation of more economical units, and partly to the paralleling of a number of very large generators in one power station. In general, efficiency is improved by whatever constitutes better engineering and management, etc.

For any given system there are a number of limiting conditions. There are also certain manufacturers'

standards established, upon which certain calculations must be based. There are certain local standards of construction and use of materials, and there are the general limitations established by accepted good practice.

Maximum Capacity. The limit to the economical size of a complete electric power system (generating system) is as yet not in sight, and the experience of recent years indicates that the economical capacity of individual units is vastly greater than the average capacity of generating units at present installed and possibly greater than that of the largest units yet built. The more economical working of the larger systems is due partly to the services of high grade engineers which the smaller systems cannot afford. An increase in the size of units, and in general, an increase in the size of systems, means a further extension of the economical size.

High engineering talent brings with it means for producing high efficiencies, reduced costs, more reliable and better service, not only for the present but for all time, because of the installation of the best and most economical units, apparatus, and auxiliaries, the best system layout, and the most nearly perfect organization and control. On the other hand, poor engineering under similar circumstances places a permanent handicap upon the enterprise which can rarely, if ever, in after years be brought to the efficiency which it ought to attain. The greater the system, the greater will be the permanent tax due to poor engineering, which once incurred cannot, economically speaking, be changed. The engineering of an enterprise, particularly during its inception, and more particularly in regard to the larger systems, should, therefore, be in the hands of experienced and competent engineers, and should receive even greater attention than the system management which can very readily be changed at little cost.

Electric power development is distinctly towards the construction of larger and still larger prime movers and generators for the production of electrical energy, and towards the parallel operation of these very large units in single power stations of great capacity. Such large systems of electric generation produce electrical energy so cheaply and, when two or more of such systems are operated in parallel, so reliably that isolated plants (in factories, mills, large hotels, etc.) are economically out of the question unless a large amount of steam heating is required. Compared with small power stations and isolated generating plant on manufacturer's premises, large electric power systems yield cheaper power for practically all industries ; they eliminate the capital expenditure, staff and space occupied by isolated plant ; they yield more reliable general service which is available at any time, and which can be enlarged and extended with minimum delay, inconvenience and cost.

Circuit Conditions. With direct current transmission the ohmic resistance of the circuit is the dominating factor. With alternating currents the effective resistance of the circuit depends upon the ohmic resistance of the conductors, the skin effect, the inductance and the capacitance effects of the line itself and of the terminal apparatus. The skin effect varies with the size of conductor and the periodicity ; for overhead lines using copper conductors it can be neglected, but for cables of large current-carrying capacity it must be taken into consideration. Inductance varies with the periodicity, the size of the conductor, the spacing of the conductors, the length of the circuit, and the *current* load. Capacitance varies with the size of conductor, the spacing of the conductors, the length of the circuit, the transmission voltage and the frequency or periodicity of supply. The inductance, like the resistance, is in series with the load current and affects the

voltage. The capacitance is in shunt with the load, and, therefore, affects the current.

Good voltage regulation means minimum losses and maximum sale of energy. The low tension pressure drop is probably the most important element in maintaining a high standard of service. This becomes apparent when it is considered that by means of voltage and power factor regulation, the voltage of the high tension mains can be controlled, and with a well-designed system under efficient operation, voltage regulators can be made to give practically constant voltage at the distribution centres. Especially is this true when lighting feeders are separate from the power feeders. Voltage regulators are not used on the low tension side, and the regulation at the load is therefore determined almost entirely by the low tension voltage drop. The percentage voltage drop varies with change in the applied voltage. In general, the voltage drop $= I \times Z$ where $I =$ current in amperes, and $Z =$ impedance in ohms; and the percentage voltage drop $= 100IZ/E$, where $E =$ normal line voltage. The value of I may be expressed differently, according to the load conditions, and the corresponding formulae for percentage voltage drop can then be tabulated as follows—

Condition.	Current.	Percentage voltage drop.	Voltage drop varies inversely with
Constant load current.	I	$\frac{100\ IZ}{E}$	E
Constant kilowatts, unity power factor	$\frac{1,000 \times \text{kW}}{E}$	$\frac{100,000\ \text{kW} \times Z}{E^2}$	E^2
Constant power factor and kilowatts	$\frac{1,000 \times \text{kw}}{E.\cos\varphi}$	$\frac{100,000\ \text{kW} \times Z}{E^2 \cos\varphi}$	E^2
Constant kilovolt-amperes.	$\frac{1,000 \times \text{kVA}}{E}$	$\frac{100,000\ \text{kVA} \times Z}{E^2}$	E^2

When determining the most economical overhead transmission voltage and designing the conductor circuit, the amount of power to be transmitted and its cost per unit are very important factors to be borne in mind. The cost of apparatus and line equipment also influence the choice of the most economical transmission voltage where the distance is of moderate length, but where the transmission distance is great the cost of conductors is or relatively greater importance. The cost of energy loss in transmission is also greatly influenced by the annual time-factor (i.e. operating hours per annum) and by the value of the load-current, because the cost per kilowatt-hour for energy lost determines more or less the most economical size of conductor. Inasmuch as the choice of a conductor and a choice of voltage are generally limited to manufacturers' commercial standards, it is neither necessary nor advisable to seek exactness in finding a solution.

CHAPTER II

SYSTEMS

The Function of Electricity Undertakings. Certain large electric power undertakings not only generate power for sale, but also purchase power in bulk from other distributing companies, and in turn sell bulk power to various other electric power systems. A power undertaking may operate its own power plants ; may operate under some agreement the plant or plants of another organization ; may operate an extensive system of power transmission and distribution ; may sell electrical energy as well as mechanical energy direct to consumers ; may sell power in bulk to subsidiary companies which it owns, some of which may operate their own generating stations ; may sell power in bulk to other independent electric generating and distributing stations ; or may sell power to isolated electric plants, etc. There is also the system which includes a number of subsidiary companies, each operating one or more generating stations, and each supplying practically its entire output to the controlling or "parent" company, which is the power distributing company controlling the selling of power, not only direct to consumers, but also in bulk to other central stations. Then there is another case in which a company operating two or more distinct systems may purchase all the energy used in connection with one or more systems, and generate part of the energy distributed over the other systems. The company may purchase the entire output of one or more plants operated by a subsidiary company, and may also purchase a large proportion of the output of another separate and independent organization. Or, it may operate one or more generating stations, and also purchase the entire output of one or more plants operated by

subsidiary companies. There are also numerous instances of operation of plants and systems in conjunction with those of isolated, industrial, and other plants.

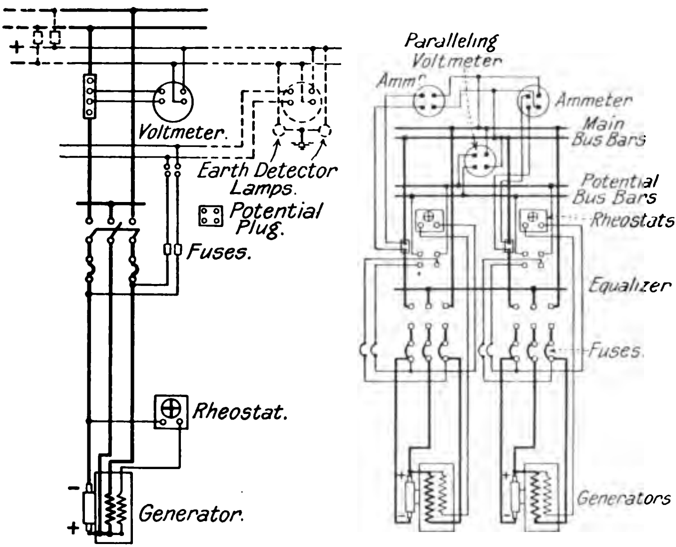
Development of Steam and Water Power Stations. The present day success of electric power transmission and distribution has been due mainly to two general applications: one where it was found necessary to generate power by steam in a single large plant in place of numerous small plants, resulting in great economy in many directions; another where the steam power plants were superseded by what were formerly considered to be commercially impracticable water powers. In this way central station plants were opened up at the large centres of population, and the electric transmission and distribution radiated far into the country, where current was supplied to railways, and to power and lighting in outlying towns. Later, there followed the more modern developments of water power in almost inaccessible regions, where vast drainage areas were studied with a view to obtaining economic storage and regulation of flow and economic development of the water thus stored and regulated for power purposes. Power in great bulk, and counted in tens of thousands of horse-power, is now brought from these mountainous regions and conveyed by overhead transmission lines into existing steam power stations or into independent stations located in or on the outskirts of the larger towns or cities. The development of water power has doubtless been retarded considerably, due to many causes, one of the most important being the rapid development and the decreasing cost of steam machinery which has come about since the introduction of the steam turbine. Other considerations are the wide variations in the stream-flow through the different seasons of the year, the great distance from the power market, and the relatively high cost of

complete hydraulic construction. Yet, allowing for all these, the water power of a country is a valuable source of wealth. It is, indeed, more valuable than deposits of fuel in that water power is continually regenerated by evaporation and rainfall, whereas coal and oil are irreplaceable. A second and even stronger reason for the utilization of water power wherever possible is that unused water power represents energy and wealth for ever lost, whereas fuel remains available for posterity until it is burned.*

Generation. The systems in general use at the present time are—(*a*) The direct current system, Fig. 1. (*b*) The single-phase system, Fig. 2. (*c*) The three-phase system, Fig. 2.

(*a*) *Direct Current System.* In this system the usual types of generators are the shunt- and the compound-wound, these terms indicating the mode of excitation. They are further classified according to the number of poles and according to the method of drive. The shunt-wound generator is used widely for lighting loads because it maintains approximately constant terminal e.m.f. at all loads. Due to the resistance and reactance in the armature the terminal e.m.f. decreases slightly with increasing load, but the field rheostat permits the field excitation to be adjusted so that constant terminal e.m.f. can be maintained. The compound-wound generator finds a very wide field of usefulness. In this machine there are two field windings—a series winding, which consists of relatively few turns of insulated conductor of sufficient sectional area to carry the entire load current without undue heating, and a shunt winding which consists of a large number of small insulated conductors. By the addition of this series winding to a shunt generator, the terminal e.m.f. can

* For further information the reader should refer to *Modern Central Stations*, by C. W. Marshall, and *Hydro-Electric Development*, by J. W. Meares, uniform with this volume, 2s. 6d. each.



(*a*) Single Generator (*b*) Two Generators in Parallel.

FIG. 1.—CONNECTIONS FROM GENERATOR TO SWITCHBOARD IN DIRECT-CURRENT CIRCUITS.

The diagrams show the connections for (*a*) a single generator, (*b*) two generators in parallel. The generators are compound-wound with 3-wire connections to the switchboard. The correct location of main fuses, instruments, etc., should be noted.

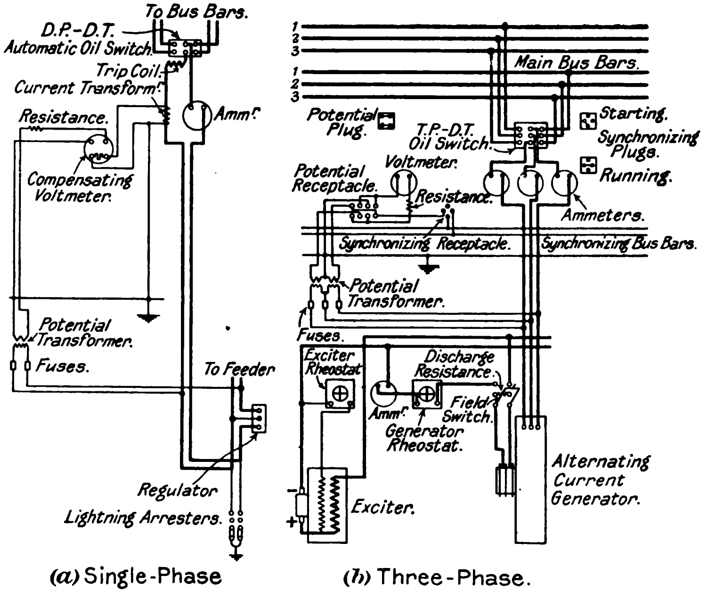


FIG. 2.—CONNECTIONS FROM GENERATOR TO SWITCHBOARD IN SINGLE-PHASE AND THREE-PHASE ALTERNATING CURRENT CIRCUITS.

The diagrams show electrical connections for (*a*) a single-phase feeder circuit starting from the station switchboard busbars; (*b*) a three-phase generator with exciter. In each case there are two sets of busbars over which supply may be obtained. All instrument circuits are earthed where instrument transformers are used.

automatically be maintained constant or, by a proper proportioning of the series winding, the terminal e.m.f. can be made to increase with load to compensate for the line voltage drop.

The series generator need not be discussed here because it is not in general use, but the series motor has a very wide field of usefulness on account of its speed-torque characteristics, which are well adapted to traction and similar requirements.

(*b*) and (*c*) *Alternating Current System.* The alternating current generator (synchronous type) is very widely used, particularly the three-phase machine. It usually consists of a number of revolving field poles excited with a direct current supply by a separate d.c. generator (exciter), and a stationary armature with coils embedded in slots in which the alternating e.m.f. is induced. In the single-phase generator one set of armature coils is provided, and in the three-phase generator three sets of coils are placed on the armature 120 electrical degrees apart, i.e. one-third of one electrical revolution, which corresponds to the circumferential distance from the centre of one pole to that of the next pole of the same polarity.

If N = armature revolutions per second, and $2p$ = the number of poles, then—

$$\text{Frequency} = p \times N$$

i.e. the frequency in cycles per second equals the product of the number of pairs of poles by the number of revolutions per second.

In the three-phase generator the windings may be connected either in star or in delta. When connected in star, with the neutral point earthed, each phase winding has the advantage that its insulation need only be made to withstand safely $1/\sqrt{3} = 57{\cdot}7$ per cent of the terminal voltage.

Circuit Conditions in Generators. In terms of *effective* voltage E, current I and power P, the direct

current (2-wire) system, the single-phase (2-wire) system, and the three-phase (3-wire) system, may be compared as in Table I.

TABLE I.—CIRCUIT CONDITIONS IN DIRECT AND ALTERNATING CURRENT SYSTEMS

	Direct current (2-wire).	Single-phase (2-wire).	Three-phase (3-wire).
Voltage between terminals . . .	E	E	E
Current per conductor or phase . .	I	I	I
Power in kilowatts .	$EI/1{,}000$	$EI \cos \varphi/1{,}000$	$\sqrt{3}\, EI \cos \varphi/1{,}000$
Voltage to neutral .	$E/2$	$E/2$	$E/\sqrt{3}$

On the basis that the current per phase-winding, in the case of the three-phase system with delta connection is I, the terminal current is $\sqrt{3}\ I$, or the vector sum of the two currents in the two phase-windings connected to the line. When the windings are star-connected, the phase current and line current are equal, but the line voltage is $\sqrt{3}$ times the phase-winding voltage, or the vector sum of the voltages in the two windings.

Whether the machine is star- or delta-connected, the three phase-voltages are equal, and the three phase-currents are equal, if the load on the three phases is " balanced." The power P^1 of each winding is $EI^1 \cos \varphi$, and the total power is—

$$P = 3\ EI^1 \cos \varphi$$

If E and I represent the *line* voltage and current respectively, the three-phase power is expressed by $\sqrt{3}\ EI \cos \varphi$.

Let the resistance per phase-winding be r, and the resistance of any two phase-windings of a star-connected machine be $r^1 = 2r$ then, in terms of total current and equivalent single-phase resistance R,

the copper loss (neglecting power factor) is $I^2R = 3i^2r$; wherein $I = i\sqrt{3}$, and the loss per phase-winding $= i^2r$, and for the three windings $= 3\ i^2r$. But the resistance per phase-winding is $r = r^1/2$, therefore $R = r^1/2$.

In the delta-connected machine, let the current in each phase-winding equal $1/\sqrt{3}$, then the equivalent copper loss is $1^2R = (i\sqrt{3})^2r$. The measured resistance between any two terminals of a delta-connected machine is that of a resistance r in parallel with a resistance $2r$, i.e. $2rr/(2r + r)$ or $2r/3$. The equivalent single-phase resistance is $r/3$, i.e. one-half of the resistance measured from terminal to terminal. The equivalent current, or the current in an equivalent single-phase machine giving the same output at the same voltage, and at the same power factor, is the current per phase or $\sqrt{3}\ I$, hence the copper loss expressed in terms of this *total* current and equivalent resistance is $(\sqrt{3}\ I)^2r = 3\ i^2r$.

Thus, the *equivalent single-phase resistance of a delta-connected machine* is that resistance which multiplied by the square of the line current (I^2) will equal the total copper loss in the circuit; this resistance is equal to one-half the measured resistance between any two conductors. The utility of the single-phase resistance is that, in many instances, it permits the calculation of three-phase circuits by the methods applicable to single-phase circuits. One simple method, when calculations are based on a balanced three-phase system, is to take only one of the phase conductors and the neutral of the system, assuming the neutral has zero resistance and impedance. In this case one-third of the total power (P) is transmitted over one conductor with current I, but the voltage to neutral is the voltage between phases divided by $\sqrt{3}$ or $(E/\sqrt{3})$. The three-phase system may also be treated as two single-phase systems, each transmitting one-half the power; i.e.

the loss or voltage drop may be determined by assuming that each single-phase circuit transmits half the power of the three-phase system. However, with the same *effective* voltage to neutral, all systems have the same copper efficiency.

The efficiency of a generator is affected by the power factor, although this variation is somewhat modified by the ratio of the constant to the variable losses in the machine. This is determined by the design of the machine. The excitation required by a generator when operating at 80 per cent power factor is nearly 50 per cent greater than that required for the same kilovolt-amperes output at 100 per cent power factor. The decrease in efficiency between 100 per cent and 80 per cent power factor for constant kilovolt-amperes in a circuit including generator, transformers and transmission line, may average about 2 per cent for the generator; 0·8 per cent for the transformers; and about 2·3 per cent for the transmission line. Voltage regulation of the system is further impaired by lower power factor, varying in different portions of the circuit. This necessitates greater excitation on the generator and results in increase of the temperature of its windings.

Transmission.* At the present time, the three systems in common use are—The *direct current* (2- and 3-wire) system; the *single-phase* (2- and 3-wire) system; and the *three-phase* (3- and 4-wire) system. There is also the two-phase system, but this is rapidly going out of existence; it is not discussed here because of this fact, and also because the use of two-phase current is no longer entertained where new installations or extensions are proposed.

The relative copper efficiency of the various

* For a treatment of the physical basis of electrical transmission, its methods and phenomena, see *Electrical Transmission of Energy*, by W. M. Thornton, uniform with this volume, 2s. 6d. net.

systems is compared in Table II, assuming 100 per cent power factor and equal power loss, delivered power, and distance of transmission.

TABLE II.—RELATIVE COPPER EFFICIENCY OF DIRECT AND ALTERNATING CURRENT SYSTEMS

(At unity power factor and for equal power loss, delivered power, and distance of transmission.)

	Direct Current.	Single-Phase.	Three-Phase.
Voltage between conductors, in per cent	100	100	100
Current per conductor, in per cent	100	100	$100/\sqrt{3}$ (= 57·7)
Total conductor weight, in per cent	100	100	75
Loss per conductor, in per cent	100	100	66·7

Underground Cables and Overhead Lines Compared. In towns and urban districts of almost any size, regulations require that all electrical conductors be put underground. Some of the *advantages of underground cable service*,* which is the common practice in this country, are—

(*a*) Absolute freedom from interruptions of service and damage to apparatus from lightning disturbances.

It is generally recognized and acknowledged that a purely underground system of electrical distribution or transmission is immune from atmospheric disturbance by lightning, although disturbances and extra high potentials due to surges, arcing earths, etc., do occur in underground cable systems.

* For information on cable construction and applications see *Electric Cables*, by F. W. Main, uniform with this volume, 2s. 6d. net.

(*b*) Less liability to interruptions from breakdowns.

In Greater London, where probably there is more underground cable than in any other city in the world, interruption of service due to the breakdown of a cable is a rare occurrence. Most of the breakdowns occurring in high tension cables are the outcome of poor workmanship, which can largely be anticipated and avoided.

(*c*) Fewer interruptions of service from extraneous interference.

Short circuits and earths are more or less frequent on overhead lines due to breaking of mechanically weak conductors or insulators, wind storms or snow, branches or other things falling across the conductors and short-circuiting them, and to malicious interference. With underground conductors, annoyances of this character are almost entirely eliminated, the cables usually being installed in ducts of tough material, enclosed in solid material (such as concrete) several inches thick, the whole being from 18 to 48 inches below the surface of the ground. The manholes are protected by double heavy iron covers, affording protection against almost anything.

Though breakdowns and interruptions in cable systems are not nearly so frequent as with overhead lines, a breakdown in a cable is nearly always more serious than in an overhead line, and the latter can be repaired more quickly and cheaper than the former.

(*d*) Greater safety of the public.

Injury or death to individuals coming into contact with broken overhead conductors are of rare occurrence, but it requires no argument to prove the greater safety of underground construction in this respect.

(*e*) Greater safety to workmen.

The danger to workmen is also less with underground than with overhead construction, because in repairing or stringing new overhead lines there are sometimes other "live" circuits with which the conductors may come in contact, whereas with underground construction all the "live" cables are enclosed in lead sheaths which are at earth potential.

(*f*) Possibility of detecting deterioration before breakdown occurs.

Breakdowns in overhead circuits, as they are designed to-day, usually occur without any warning. In a cable system, the weakening of the insulation of cables is often determined by tests or by suitably designed apparatus, sufficiently in advance of the actual breaking down of the insulation to allow the load

to be transferred to another cable without interruption of service. Such apparatus or devices also take into account the unbalancing of the current in the cable, when the insulation of the cable begins to depreciate and give warning of approaching danger sufficiently in advance of a breakdown to allow the cable to be disconnected.

Both the overhead and the underground systems have now reached a high degree of perfection, but owing to the fact that overhead conductors are exposed, they are necessarily more subject to breakdowns ; we may, therefore, conclude that the underground system is preferable from the point of view of superior security of supply.

The advantage of overhead power lines lies in their relative capital cost, more particularly at the higher voltages. As the voltage, transmission distance and size of conductors increases, a considerable saving is effected by the construction of overhead lines, and such a saving is sometimes increased by the difficulty of the route or the finding of a direct route for the underground cable in country districts where roads are few and winding.

Due to the relatively low first cost of overhead lines, their durability, and their ability to give satisfactory power service, they are universally used for transmission purposes. Unfortunately, *overhead lines have certain electrical disadvantages*, viz.—

(*a*) Inductive drop much greater than in underground cable of equal length.

The inductance of an alternating current circuit (*see* Fig. 5), other factors remaining constant, varies as the logarithm of the distance between the line conductors ; the higher inductance of the overhead line is, therefore, inherent in its construction, since the distance between conductors must be many times the corresponding distance in a cable, owing partly to the lower insulating value of air as compared with impregnated paper, but more particularly to the necessity for preventing accidental short-circuiting of the conductors by swinging together, etc. This higher inductance does not affect the voltage drop when

the power factor of the system is not a lagging one, but this is of rare occurrence.

(*b*) Tendency to lower the power factor of the system as a whole.

It is evident that, so far as the power station and the transmission lines are concerned, the wattless current produced by the extra inductance in the overhead lines will be as harmful as if it were produced by the consumers' apparatus.

(*c*) Parallel operation between overhead and underground circuits is not economical.

If an overhead line and cable of equal sectional area and length be connected in parallel, the much higher inductance of the overhead line causes the total current to divide unequally between the two circuits. This difference in impedance not only prevents the two circuits from being operated at their most economical current density, but also, owing to the resistance losses being dependent on the square of the current, they are greater than if the current were divided equally. Also, owing to the difference in the inductance of the parallel circuits, there is a phase difference between the currents in the two branches. This results in the arithmetical sum of the currents in the branches being greater than the total current, thus causing additional resistance losses and a reduction in the carrying capacity of both the overhead and the underground circuits.

Thus, from the electrical standpoint, there are several advantages in favour of the underground system.

Power Loss and Voltage Drop in Line. The evil effects of line inductance (*see* Fig. 5) and impaired power factor (*see* Fig. 3) are too well known to need much discussion. Every kilowatt of I^2R loss means a loss extending right back to the coal pile ; it means that lines and apparatus are over-loaded, that every motor on the system is working under the handicap of poor regulation, and that the income of the power undertaking is reduced just at the time when the consumer is willing to pay almost any reasonable price in order to get increased power. The effect

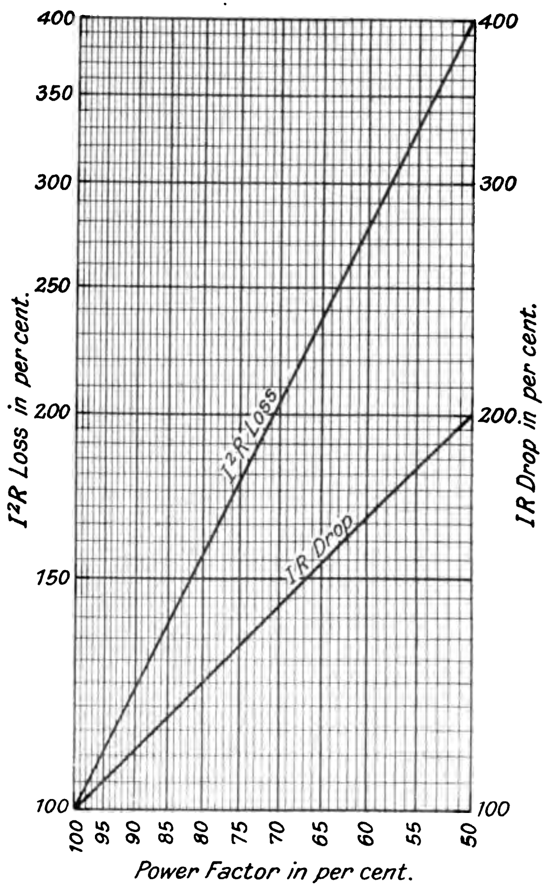


FIG. 3.—SINGLE-PHASE POWER LOSS AND VOLTAGE DROP DUE TO POWER FACTOR.

This chart makes clear the detrimental effects of low power factor. The voltage drop varies inversely with the power factor and the power loss varies inversely with the square of the power factor. Thus, at 50 per cent power factor the IR drop is twice as great, and the I^2R loss is four times as great as at 100 per cent power factor.

of power factor on power loss and voltage drop is shown in Fig. 3.

Energy lost in the line could presumably have been sold at the same price as the rest of the energy, so that, broadly speaking, the most economical transmission is one which is so designed that an increase in the amount of copper would cost more in interest, etc., than the market value of the additional energy thus rendered available, whilst a decrease in the amount of copper would reduce the interest charges by a less amount than the loss of income due to the increased energy loss. This is along the lines of Kelvin's Law.

At light loads the (overhead) line power factor is usually worse, but the line resistance loss is reduced, though not in proportion to the load because, for any particular load, the line current increases as the power factor decreases. Also, the ohmic resistance of the line, with constant load current in the line, varies with the temperature of the surrounding air. There is thus, due to these causes, a variation in the value of the product $R \cos \varphi$ at different periods of the day and night.

A convenient way of arriving at the *comparative amount of copper required* for the different systems of transmission is to add the currents in the separate conductors, without regard to their phase or directions, and to assume that this total current is transmitted one way only over one conductor composed of all the copper in all the actual conductors of the system. This method is *not* applicable to the calculation of voltage drop.

Power Loss. Let I represent the current in each conductor and R the resistance of each of the two conductors of a *single-phase* or *direct current* (2-wire) transmission. Then I^2R equals the power loss in each conductor and $2I^2R$ the power loss in both conductors. Using the method suggested above, the sum of the current in the two conductors is $2I$ and

the resistance of the two conductors in parallel is $R/2$, hence the power loss due to carrying the total current one way in a single conductor containing all the copper is $(2I)^2 \times (R/2) = 2I^2R$.

In a balanced *three-phase* (3-wire) transmission, carrying current i per line of resistance r, the total current is $3i$, and the resistance of all the conductors in parallel is $r/3$, hence the power loss is $(3i)^2 \times (r/3) = 3i^2r$.

In comparing the amounts of copper that must be used to transmit equal amounts of power at the same voltage between conductors, assuming, as in the above, a power factor of unity, it will be seen that the current I per conductor in the single phase system equals $i\sqrt{3}$, where i = current per conductor in the three-phase transmission. The total current for the single-phase transmission is $2I$, and that for the three-phase transmission is $3i$ or $I\sqrt{3}$. The corresponding power losses are $(2I)^2\ (R/2) = 2I^2R$ in the single-phase system and $(I\sqrt{3})^2\,(r/3) = I^2r$ in the three-phase system, where R = resistance per conductor in the single-phase system and r = that in the three-phase system. In order that the power loss may be equal in the two cases $2R = r$, i.e. the single-phase conductors must be of half the resistance and therefore twice the cross-section of the three-phase conductors. There are, however, two single-phase conductors and three three-phase conductors, so that the relative total weights of copper are $2 \times 2 : 3 \times 1$, i.e. $4 : 3$. In other words, the three-phase transmission requires only 75 per cent as much copper as the single-phase or direct current (2-wire) transmission under the conditions stated.

Voltage Drop. (i) At unity power factor the voltage drop is—

In a single-phase line, $2\,IR$;
In a three-phase line, $\sqrt{3}\ IR$,
where I = line current, and R = resistance of one line.

(ii) With a load of lagging power factor, the voltage drop is—

In a single-phase line, $2I(R\cos\varphi + X\sin\varphi)$;
In a three-phase line, $\sqrt{3}\,I(R\cos\varphi + X\sin\varphi)$;
where I = line current; R = resistance of one line; and X = inductive reactance per conductor.

The voltage between neutral and line at the generating end of the line is expressed by—

$$\sqrt{\{(E\cos\varphi + RlI)^2 + (E\sin\varphi + XlI)^2\}}$$

where E = voltage at receiving end, measured between neutral and line in the case of three-phase transmission;
l = length of line, in miles, one way;
I = line current, in amperes;
R = resistance, in ohms per mile;
X = reactance, in ohms per mile;
$\cos\varphi$ = power factor at receiving end;
$\sin\varphi$ = reactance factor = $\sqrt{(1-\cos^2\varphi)}$.

This expression may be put in the form—

$$E\sqrt{\left\{\left(\cos\varphi + \frac{R}{Z}\right)^2 + \left(\sin\varphi + \frac{X}{Z}\right)^2\right\}}$$

where R and X have the same meanings as before and Z = impedance in ohms per mile.

Denoting the voltage at the generating end by Eg and at the receiving end by Er, the percentage voltage drop in the line referred to, the received voltage, is—

$$\text{Percentage drop} = \frac{Eg - Er}{Er} \times 100$$

$$= 100\left[\sqrt{\left\{\left(\cos\varphi + \frac{R}{Z}\right)^2 + \left(\sin\varphi + \frac{X}{Z}\right)^2\right\}} - 1\right]$$

The *efficiency of transmission* may be expressed—

$$\eta = \frac{Er\,I\cos\varphi}{Er\,I\cos\varphi + I^2R}$$

The percentage regulation of a single-phase or three-phase line on *non-inductive load* is obtained by

adding arithmetically the percentage resistance volts and the percentage reactance volts.

If R = total resistance of one conductor from generator to receiver;
X = total reactance of one conductor from generator to receiver;
I = amperes per conductor at *non-inductive* full-load;
and E = voltage between conductors;

then, *percentage resistance-volts* is—
For a single-phase line, $2\ (IR/E)$;
For a three-phase line, $\sqrt{3}\ (IR/E)$;

and the *percentage reactance-volts* is—
For a single-phase line, $2\ (IX/E)$;
For a three-phase line, $\sqrt{3}\ (IX/E)$.

The *percentage regulation* is therefore—
For a single-phase line, $2\ [(IR/E) + (IX/E)]$.
For a three-phase line, $\sqrt{3}\ [(IR/E) + (IX/E)]$.

Where the system consists of step-down transformers, transmission line, and step-up transformers, all that is necessary is to take the percentage resistance and reactance volts of each group of transformers and the transmission line, and *add* the percentage resistance-volts and also the percentage reactance-volts then using the above equation for percentage regulation with non-inductive load, just as though this resistance and reactance were all in the transmission line.

The impedance factor of a circuit increases with the size of conductor at any given spacing because the resistance decreases in proportion to the area, and the length of the circuit is not concerned since both resistance and inductance increase directly with the length so that they remain proportional. The impedance can be expressed in terms of resistance by multiplying the resistance by the proper impedance-factor, also, the same factor converts the

ohmic drop into impedance drop. For low power factor not only does the impedance ratio rise, but the resistance drop increases for the same power (*see* Fig. 3), so that the regulation is made worse. The regulation, i.e. the voltage variation at the receiving end with different load conditions constitutes a very important electrical factor in alternating current work, much more so than in direct current work because of the non-inductive and inductive effects in the circuit itself. The voltage drop in the line is not only the loss of voltage between the generator and the load ; in addition there is the loss in the step-up and the step-down transformers, as well as the secondary apparatus and distributing network. All things considered, the variation of voltage should be made as small as practicable, and as the distribution and the transmission lines represent the largest part of the total voltage drop and can be controlled to some extent, the total voltage drop in the lines should be kept low, that is, within about 10 per cent total. Calculations are usually made for power loss, voltage drop, cost of copper, and the cost of other parts of the circuit for a given set of assumptions as to voltage, frequency, and size of conductor, the effect of varying the voltage or the size of conductor being then examined to see if a better set of conditions can be found. Both power loss and voltage drop are very closely linked with the transmission voltage which should always be chosen as high as possible without greatly increasing the cost of the apparatus, etc., affected by the voltage increase.

Capacity and Charging Current. Underground cables are now in successful operation at very high voltages, up to 60,000 V for single-core and 33,000 V for 3-core cables. The insulation is generally protected by a lead sheath, or by a lead sheath and armour tape. For alternating current service all

the conductors of the circuit are usually in one cable, as the currents in the different conductors then neutralize the tendency to set up eddy currents in the sheath which is always well earthed to allow the high voltage static charges to pass readily to earth. Different from an overhead transmission, the electrostatic capacity of an underground transmission is usually high and the inductance almost negligible. In extensive high voltage cable systems it is not uncommon to find the charging current equal to 50 per cent of the load current.

In overhead transmission systems the *capacity* C in microfarads per mile is given by the formulæ—

	Single-phase.	Three-phase (between line and neutral).
$C =$	$\dfrac{0{\cdot}0194}{\log(D/r)}$	$\dfrac{0{\cdot}0388}{\log(D/r)}$

where C = capacity, in microfarads per mile ;
D = distance between conductors, in inches ;
r = radius of conductor, in inches.

and the *charging current* I_c in amperes is given by—

	Single-phase.	Three-phase (in each conductor).
$Ic =$	$\dfrac{2\pi f E C l}{1{,}000{,}000}$	$\dfrac{2\pi f E C l}{1{,}000{,}000\sqrt{3}}$

where Ic = charging current in each conductor, in amperes ;
f = frequency, in cycles per sec. ;
E = p.d. between conductors at generator end, in volts ;
C = capacity, in microfarads per mile ;
l = length of line (one way), in miles.

It will be seen that the capacity per mile is twice as great between line and neutral in a three-phase system as between lines in a single-phase system. Also, the charging current *for equal capacity* is $I\sqrt{3}$ times as great in each three-phase conductor as in each single-phase conductor ; hence, allowing for the actual

difference in capacity, the charging current of a three-phase circuit is $2/\sqrt{3} = 1{\cdot}155$ or 15·5 per cent greater than that in a similar single-phase circuit.

For equal length, the capacity of underground transmission systems is much greater than that of overhead transmission systems because the distance between conductors is much smaller in the case of cables and because the specific inductive capacity of the insulation between the conductors of cables is higher than that of air.

The high voltage direct current series system and the two-phase alternating current systems are not considered here. In English-speaking countries the former is practically non-existent, and the two-phase system is fast giving way to the more economical three-phase system.

Calculation of Size of Conductors. Two considerations have to be taken into account, viz. the voltage drop in the line and the current density in the conductors. Having calculated the size of conductor for any given voltage drop, it must be confirmed that this size of conductor can safely carry the desired current.

The *current per phase* in a three-phase system may be calculated from whichever one of the following formulæ is more convenient—

$$\begin{aligned} I &= 1{,}000 \times \text{kVA}/(E\sqrt{3}) = 577 \times \text{kVA}/E\,; \\ &= 577 \times \text{kW}/(E \cos \varphi)\,; \\ &= 43{,}000\ HP/(\eta E \cos \varphi)\,; \end{aligned}$$

where I = amperes per phase;
kVA = kilovolt-amperes input to line;
kW = kilowatts input to line;
E = volts between lines at generator end;
$\cos \varphi$ = power factor;
HP = horse-power output of machine supplied;
η = efficiency of machine supplied, in per cent (*not* as a decimal).

The *size of conductor* required for any system of transmission may be calculated from the general formula—

$$A = \frac{\mathrm{kW} \times l \times n}{E_r^2 \times e \times \cos\varphi}$$

where A = cross section of conductor, in sq. in.;
kW = power delivered, in kilowatts;
l = length of line (one way only), in miles or yards (*see* n);
E_r = volts between lines at load end of line;
e = voltage drop, in per cent (*not* as a decimal);
$\cos\varphi$ = power factor;
n = a numerical factor as follows—

Transmission System.	Value of n.	
	l in miles.	l in yards.
Continuous current or single-phase (2-wire) . . .	8,800	5·0
Three-phase, star or delta, 3-wire	4,400	2·5
Three-phase, 4-wire; V *being measured between outer and neutral in this case* . .	1,470	0·833

EXAMPLE. *Suppose that it is desired to transmit* 4,000 *kw. a distance of* 10 *miles over a three-phase* (3-*wire*) *line, the delivered voltage being* 16,500 *V, the voltage drop at full-load* 8 *per cent, and the power factor* 0·8. *What is the cross section of conductor required?*

By substitution in the formula for A, we have—

$$A = \frac{4000 \times 10 \times 4400}{(16500)^2 \times 8 \times 0{\cdot}8} = 0{\cdot}10 \text{ sq. in.}$$

If the percentage pressure drop, or the delivered voltage, be the unknown factor it is only necessary to transpose the formula for A thus—

$$e = \frac{\mathrm{kW} \times l \times n}{E_r^2 \times A \times \cos\varphi}$$

$$E_r = \sqrt{\frac{\mathrm{kW} \times l \times n}{A \times e \times \cos\varphi}}$$

the symbols having the meanings stated above.

The chart shown in Fig. 8 (p. 72) may conveniently be used to determine the size of conductor corresponding to any specified voltage drop per mile.

EXAMPLE. Assuming the same basic data as before, the current per conductor = $577 \times \text{kW}/E \cos \varphi = 577 \times 4{,}000/16{,}500 \times 0{\cdot}8 = 175$ A. From the chart (Fig. 8) the corresponding voltage drop, in a 0·10 sq. in. conductor, is 75 V per mile, hence the total drop in 10 miles = $75 \times 1{\cdot}76 \times 10 = 1{,}320$ V = 8 per cent of 16,500 V.

If the percentage voltage drop be the known factor, the chart can be used to determine the sectional area of the conductor.

Working with the percentage power loss p (instead of the percentage pressure drop) the above formula for A may be put in the form—

$$P = \frac{\text{kW} \times l \times n}{E_r^2 \times A \times (\cos^2 \varphi)}$$

which, in the example chosen, gives

$$p = \frac{4000 \times 10 \times 4400}{(16500)^2 \times 0{\cdot}10 \times (0{\cdot}8)^2}$$
$$= 10{\cdot}1 \text{ per cent.}$$

Knowing the percentage power loss, the power factor, the distance of transmission, and the delivered load and voltage, the size of conductor may be found, in terms of its *weight per mile*, from the formula—

$$\left.\begin{array}{l}\text{Weight of single}\\ \text{conductor per}\\ \text{mile, in lbs.}\end{array}\right\} = \frac{kW \times D \times N}{E_r^2 \times p \times (\cos^2 \varphi)}$$

where $N = 91{,}000{,}000$ for copper conductors in a three-phase, 3-wire circuit; and the remaining symbols have the meanings already stated.

Thus, choosing the same example as before, if 4,000 kW be delivered at 16,500 V and power factor 0·8 at the end of a 3-phase line 10 miles long, in which the power loss is 10·1 per cent—

$$\left.\begin{array}{l}\text{The weight of single}\\ \text{conductor per mile}\end{array}\right\} = \frac{4000 \times 10 \times 91{,}000{,}000}{(16{,}500)^2 \times 10{\cdot}1 \times (0{\cdot}8)^2}$$
$$= 2{,}050 \text{ lbs.}$$

The weight per mile of 3-phase circuit is $3 \times 2{,}050 = 6{,}150$ lbs., and the total weight of copper in the 10 miles of 3-phase line is $10 \times 6{,}150 = 61{,}500$ lbs.

From any manufacturer's tables of copper conductors it

can be seen that a weight of 2,050 lbs. per mile of single conductor lies between the weights of two standard sizes of stranded conductor, viz. 0·10 sq. in. and 0·094 sq. in.

The *weight per mile of three-phase* (3-*wire*) *annealed copper conductors* is 60 lbs. per 0·001 sq. in. of conductor cross section. Hence in the above case, where the weight per mile of three-phase circuit = 6,150 lbs., the sectional area per conductor = (6150/60) × 0·001 = 0·10 sq. in., very nearly. This rule is very convenient where no tables are available.

Transformers.* Transformers as referred to herein are for transforming electrical energy from one potential to another. As generally built, this apparatus consists of three distinct parts, the primary winding which magnetically energizes the second part called the core; this latter in turn induces a voltage in the secondary winding or third part. The power (EI) is, neglecting the losses, exactly equal on each side of the transformer, that is, if the voltage E is 20 times as high on one side as it is on the other, then the current is only one-twentieth as great.

Transformer Losses and Cooling. When electrical energy is transformed from one voltage to another a certain amount of energy is transformed into heat energy, due to three losses, namely: *core losses* in the iron, *copper losses* in the windings due to their ohmic resistance, and *eddy current losses* due to circulating currents induced in the windings, the tank, and other metal parts of the transformer.

The core loss depends only upon the magnetic induction and the frequency and is therefore nearly constant. The copper loss originates only in the windings and varies proportionally as the square of

* See also *High Voltage Power Transformers*, by the Author uniform with this volume, 2s. 6d. net.

the current (I^2). The eddy current loss is, in well-designed transformers, usually very small.

The continual generation of heat in the transformer, due to its losses, makes necessary proper means of cooling, in order to keep the temperature within reasonable economical limits.

The *self-cooled* oil-immersed transformer is especially applicable for substations where help or water is expensive. Its first cost is relatively higher than that of other types, but this should be balanced against the cost of attendance and auxiliary apparatus of the water-cooled type. It can be built for operation at the highest commercial voltage.

The *water-cooled* type is the most extensively used at the present time for very large power service owing to its being smaller and cheaper than other types, per unit output. For power distribution work, and medium-size power stations (indoor and outdoor types), the self-cooled type is used almost exclusively. For conditions where long and definite periods of light and heavy loads occur, a combination of the self-cooled and water-cooled design is becoming attractive. Such transformers are now being placed in ordinary sheet steel tanks of the self-cooled design excepting that they have smaller surfaces and are in addition provided with water-cooling coils. They can be designed to carry 50 per cent of the maximum load without water circulation and not exceed the rated temperature rise.

The *forced-oil circulation* type of transformer is rarely used.

The *air-blast* type is especially applicable to *indoor* substations, and is used extensively in converter stations. Its cost is nearly the same as that of the self-cooled oil-immersed type. Its voltage is limited by corona and dielectric heating to about 35,000 V.

The most recent development is the *outdoor type* of transformer which has proved very successful for

the highest commercial voltages. It has long since been known that one of the most important factors in determining the output of transformers is the arrangement of cooling. When transformers are situated outdoors or with abundant air-space around them and free ventilation, the problem presents less difficulty, but when they are placed in underground chambers or in transformer compartments where the atmospheric temperature is usually high and the means of conveying away radiated heat is limited, difficulties are sure to arise.

Under ordinary conditions the rate of oil circulation in transformers does not exceed about 6 ft. per min., so that the resistance to flow due to the use of coil-spacers (ventilating wave-shaped spacers) is so very slight as to have no appreciable effect upon the temperature. Generally the difference in oil temperature at the top and bottom of the windings of a well-designed transformer is from 6° C. to 10° C. for all the oil-immersed types.

Of all the features effective in modifying the design of a large power transformer there is none that so fundamentally affects it in every way as does the method used for cooling. Moreover, cooling is also most intimately associated with the first cost and with the conditions of operation.

Current, Voltage and Power Relationships. For medium and large power service, polyphase power transformation (three-phase) is used almost exclusively. For operation on high voltages the star connection generally is preferred for the reason, among others, that the transformers need only be insulated to withstand safely $E/\sqrt{3}$ or 58 per cent of the line voltage when the neutral is earthed.

The formulæ on page 33 express the current, voltage, power, and power loss relationships in three-phase circuits, *at unity power factor*.

(1) *Star Connection*—

$E = e\sqrt{3}$
$I = i = P/E\sqrt{3}$
$p = ei = EI/\sqrt{3}$
$P = 3p = EI\sqrt{3}$
Power loss $= 3\ I^2R$

(2) *Delta Connection*—

$E = e$
$I = i\sqrt{3}$
$p = ei = EI/\sqrt{3}$
$P = 3p = EI\sqrt{3}$
Power loss $= 3i^2r$
$= I^2r$

Where—

E = voltage between any two lines;
e = voltage of any phase winding
I = line current ;
i = current of any phase winding
P = total power ;
p = power of one-phase winding ;
R = resistance per phase in a star-connection ;
r = resistance per phase in a delta-connection.

Distribution. The two general distributing systems in common use to-day are the direct current and the alternating current systems, classified as—

(*a*) Direct current (2- and 3-wire); *see* Fig. 4 *A* and *A′*.

(*b*) Single-phase current (2- and 3-wire); *see* Fig. 4 *A* and *A′*.

(*c*) Two-phase current (3- and 4-wire); *see* Fig. 4 *B* and *B′*.

(*d*) Three-phase current (3- and 4-wire); *see* Fig. 4 *C* and *C″*.

The relative amounts of copper required for the different distribution systems are as shown in Table III for different power factors—

TABLE III.—RELATIVE AMOUNTS OF COPPER REQUIRED FOR DIFFERENT DISTRIBUTION SYSTEMS

(Based on equivalent total weights for the same percentage drop)

System.	Power Factor of Load.			
	100%.	90%.	80%.	70%.
(*a*) Direct current (2-wire) .	100	100	100	100
,, ,, (3-wire) .	31·2	31·2	31·2	31·2
(*b*) Single-phase (2-wire) . .	100	111	125	143
,, (3-wire) . .	31·2	35	39	45
(*c*) Two-phase (3-wire) . .	85·4	95	105	122
,, (4-wire) . .	100	111	125	143
(*d*) Three-phase (3-wire) . .	75	83	94	107
,, (4-wire) . .	29·3	32·5	36·5	42

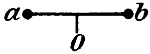
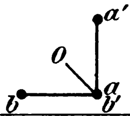
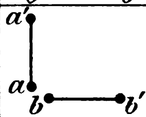
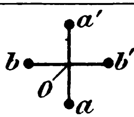
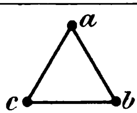
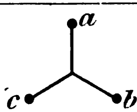
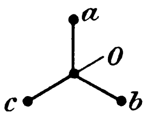
	SYSTEM.	DIAGRAM. *0 = earth connection.*	VOLTAGE.	CURRENT.
A	Direct current or Single-phase two-wire.		$ab = 2e$	$a = b = I$
A′	Direct current or Single-phase three-wire.		$ab = 2e$ $a0 = b0 = e$	$a = b = I$
B	Two-phase, three-wire.		$aa' = bb' = 2e$ $a'b = 2\sqrt{2}e$	$a' = b = I$ a (or b') $= \sqrt{2}I$
B′	Two-phase, four-wire. (Phases distinct.)		$aa' = bb' = 2e$	$a = a' = I$ $b = b' = I$
B″	Two-phase, four-wire. (Neutral earthed)		$aa' = bb' = 2e$ $a0 = a'0 = e$ $b0 = b'0 = e$ $ab = a'b' = e\sqrt{2}$	$a = a' = I$ $b = b' = I$
C	Three-phase, three-wire. Delta.		$ab = e$ $bc = e$ $ca = e$	$a = I\sqrt{3}$ $b = I\sqrt{3}$ $c = I\sqrt{3}$
C′	Three-phase, three-wire. Star.		$ab = e\sqrt{3}$ $bc = e\sqrt{3}$ $ca = e\sqrt{3}$	$a = I$ $b = I$ $c = I$
C″	Three-phase, four-wire. (Neutral earthed.)		$ab = e\sqrt{3}$ $bc = e\sqrt{3}$ $ca = e\sqrt{3}$ $a0 = e$ $b0 = e$ $c0 = e$	$a = I$ $b = I$ $c = I$ $0 =$ zero (for balanced currents)

FIG. 4.—VOLTAGE AND CURRENT RELATIONS IN THE FOUR TRANSMISSION SYSTEMS.

A. Direct current and single-phase. B. Two-phase. C. Three-phase.

Useful circuit constants for the three most common systems, are given in Table IV.

TABLE IV.—CIRCUIT CONSTANTS FOR DIRECT AND ALTERNATING CURRENT SYSTEMS

Quantity.	Symbol.	Direct Current.	Single-phase.	Three-phase.
Voltage between lines	E	E	E	E
Actual or true power	P	EI	$EI \cos \varphi$	$EI \sqrt{3} \cos \varphi$
True power loss	p	eI	$eI \cos \varphi$	$eI \sqrt{3} \cos \varphi$
" "	p	I^2R	$I^2Z \cos \varphi$	$I^2Z \sqrt{3} \cos \varphi$
Total current per conductor	I	I	I	I
True current per conductor	–	P/E	P/E	$P/E \sqrt{3}$
" " "	–	I	$I \cos \varphi$	$I \cos \varphi$
Wattless "current" per conductor	–	—	$I \sin \varphi$	$I \sin \varphi$
Voltage drop	e	IR	IZ	IZ
Impedance per conductor	Z	—	$e/2I$	$e/(I \sqrt{3})$
Per cent voltage drop	–	$100\ e/E$	$100\ e/E$	$100\ e/E$
Per cent efficiency		$100\ P/(P-p)$	$100\ P/(P-p)$	$100\ P/(P-p)$

(*a*) DIRECT CURRENT DISTRIBUTION. This system of distribution is best adapted to use where the distances are relatively small, where large industrial establishments or large buildings and hotels are concerned, or where similar congested load with storage battery reserves become necessary to ensure more reliable service. This system is of greatest importance where there is a great demand for variable speed motors. In the case of a scattered district, where the consumers are small and comparatively far apart, the cost of laying down a low-voltage distribution might be excessive, and it might be more economical in copper and apparatus to transmit electric energy at high voltage than at low voltage.

To transmit a given power over a given distance with a given percentage voltage drop (IR), or a given

percentage power loss (I^2R), the amount of copper required varies inversely as the square of the voltage between line conductors.* Hence, for scattered areas a single-phase or a polyphase distribution with transformers may be more economical than the direct current system. In congested areas, where large cables are in use carrying heavy currents, the direct current distribution system is necessary and advisable because it obviates the inductive voltage drop in single-conductor cables which is very excessive where the conductors are spaced far apart as in overhead lines. This inductive voltage drop interferes with voltage regulation in the case of alternating current distribution.

ALTERNATING CURRENT DISTRIBUTION. With the direct current system voltage drop is simply that due to ohmic resistance (R) of the conductors. In an alternating current system, however, voltage drop is caused by resistance (R), inductance (L), and capacity (C). The values of L and C respectively are given by—

$$L = [80{\cdot}5 + 741 \log (D/r)] \times 10^{-6}$$
$$C = 0{\cdot}03883/\log (D/r)$$

where = self induction of line, in henries per mile
C = star-capacity of three-phase line, in microfarads per mile
D = distance between wires, in inches
r = radius of wire, in inches

The component of voltage drop due to the resistance is governed by the same laws which govern the direct current system, but the component due to inductance is a counter-e.m.f. set up by the magnetic field as it reverses with each alternation of frequency f. The alternating current reactance in ohms is expressed by $X = 2\pi f L$; where f = frequency in cycles per

* If the voltage is doubled, the same line conductor can transmit four times the energy; at triple the line voltage the line can transmit nine times the energy with the same percentage power loss, and so on.

sec., and L = inductance in henries. The inductive drop (IX) is a very important factor, especially in heavy current lines working at a low voltage, and circuits may be rendered commercially impracticable, even for transmitting moderate quantities of power over quite short distances, on account of this drop. Hence the superiority of direct current supply in such cases. In the cable systems generally used, this inductive effect is of little consequence, more particularly where the three-phase 3-core cable is used.

(*b*) *Single-phase Distribution.* In general, single-phase distribution is used for lighting and for relatively small power service. With the exception of the congested districts of towns, where power is distributed more economically as direct current, practically all energy for lighting and small motors is transmitted from stations at high voltage to the centres of distribution and from there to transformers which step the voltage down to the voltage required on the consumers' premises. If the distribution is 3-wire, the transformers are so designed that the secondaries or low voltage windings will deliver power at the higher voltage (220 V or 440 V); the middle or neutral wire being connected to the centre of this winding. Apart from its simplicity, the single-phase system does not possess any outstanding advantage, and in view of the universal use of polyphase generation, transmission and distribution of electric power for general purposes, it is doubtful whether a purely single-phase system for similar purposes is financially worth while as regards economic production and delivery of power. It is universally recognized that three-phase generation and transmission is most efficient, flexible and economical, and the problem with the single-phase system is to compete with such important and desirable conditions.

Single-phase power may be obtained in many different ways, such as: (i) Single-phase generation, transmission and distribution; (ii) Polyphase

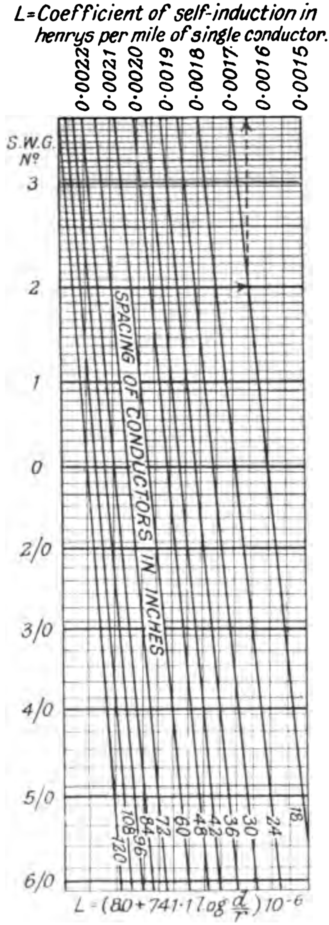


Fig. 5.—Coefficient of Self-induction for Various Sizes and Spacings of Overhead Conductors.

Example. **The self-induction per mile of single No. 2 S.W.G. conductor, spaced 18 ins. from a similar conductor = 0·00165 henry.**

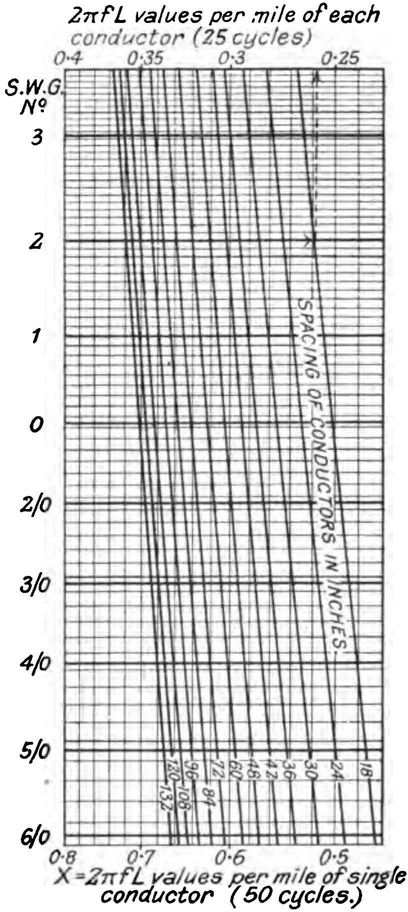


Fig. 6.—Inductive Reactance for Different Sizes and Spacings of Overhead Lines.

Example. The reactance per mile of single No. 2 S.W.G. conductor spaced 18 ins. from a similar conductor is 0·259 ohm at 25 cycles per sec., and 0·518 ohm at 50 cycles per sec.

generation and distribution of single-phase load between the phases so that in effect the load becomes a polyphase load. (iii) Polyphase generation and transmission to motor-generators consisting of polyphase motors driving single-phase generators. (iv) Mixed single-phase and polyphase load supplied by the same distribution system in combination with methods for correcting the unbalancing effect of the single-phase load, etc.

(*c*) *Two-phase Distribution.* The principal advantage in the two-phase system is that there are only two phases to keep balanced and only two single-phase transformers are required to supply polyphase power. The two-phase, 4-wire distribution is practically the same as two independent single-phase circuits. In the two-phase, 3-wire system, the inductive drop on the middle or third conductor produces an unbalanced voltage at the load if the latter is not evenly divided between the two phases. The three-phase, 3-wire system is rapidly taking the place of this system. For equal energy loss, under the same conditions of voltage and power delivered, a single-phase circuit will carry one-half the power, and a two-phase 4-wire circuit will carry the same amount of power as a three-phase 3-wire circuit having the same size of conductor. To calculate a two-phase circuit, it is usual to find the size of conductor for a three-phase circuit of equal capacity, and to the corresponding weight add 33·3 per cent to allow for the fourth conductor of the two-phase system.

(*d*) *Three-phase Distribution.* The percentage energy loss and the percentage voltage drop of a three-phase, 3-wire distributing circuit will be the same as those for a single-phase, 2-wire circuit transmitting one-half of the amount of power over two conductors of the same size and with the same spacing as any pair of the three conductors of the three-phase circuit ; assuming that in the three-phase

circuit, the three conductors are placed at the apexes of an equilateral triangle. The three-phase, 3-wire system is used very extensively for general distribution work. The three-phase, 4-wire system has several advantages over the three-phase, 3-wire system, the chief points of superiority being the $\sqrt{3}$ times increased voltage and the better balance maintained where lighting is taken off the different phases, as the neutral or fourth wire carries the unbalanced current.

As shown by Table III (p. 33), the three-phase, 4-wire system is the most economical as regards weight of conductors required. If the voltage to neutral in this system be equal to the voltage between conductors in the single-phase, 2-wire; two-phase, 4-wire; and three-phase, 3-wire systems, then the voltage between phases is $\sqrt{3}$ times as great in the three-phase, 4-wire system as in the three-phase, 3-wire system. Hence, with the same load and the same permissible power loss the size of conductor in the three-phase, 4-wire system is about one-third of that required for the three-phase, 3-wire system (see Table III).

In the three-phase, 4-wire system the star connection of transformers offers several important advantages. Without the increased voltage between mains the system would require as much copper as a single-phase circuit, and the increased voltage without the star connection would destroy the simplicity of regulation and also the advantage of supplying current for any class of service (light, power, or heating) from one phase of the star-connected transformers. Regardless of load balance on the three phases, a single-phase feeder-regulator installed in any phase can be adjusted to give a constant voltage at any point of the main. Both light and power may be taken off the same phase regardless of the load on the other phases. As required, a single-phase feeder-regulator may be installed in another phase, or three regulators may be installed, one in

each phase. The ability to regulate voltage independently on the different phases with greatly unbalanced loads makes possible the satisfactory use of single-phase distribution without affecting the advantage of three-phase feeder transmission. Supplying current for both light and power purposes not only tends to improve the power factor of the power load, but the improved diversity of demand between the power and lighting loads also makes possible a considerable saving in feeder capacity where the lighting load is of the same order of magnitude as the power load; generally the power load is quite low before the lighting peak comes on.

Primary and Secondary Feeders and Service Mains. The distribution system for either power or lighting usually consists of primary feeders to centres of distribution; secondary feeders supplying the transformers; and secondary mains supplying the service to consumers either directly or indirectly through other circuits. *Primary feeders* run direct from the station to centres of distribution with few or no taps on them; they are usually installed in trunk ducts, and therefore are less subject to damage than the other cables and are easily replaced; they derive the most benefit from the diversity factor, therefore it is not necessary to provide a great amount of reserve capacity as other feeders can be added as the demand increases. The *secondary feeders* run from the centres of distribution to the various transformers. In the smaller systems, secondary feeders are not required as the transformers are connected directly to the primary feeders. These cables are usually given ample reserve capacity to provide for all the growth that can reasonably be expected. They receive less benefit from the diversity factor than do the primary feeders. The *secondary mains* are the most important, therefore it is advisable to have them of ample size to provide for the total load and

to maintain satisfactory voltage for all consumers connected to them. Trouble on a secondary main is liable to interrupt service to every consumer spliced to it, and requires considerable time and is expensive to repair.

Faults on underground systems usually affect more consumers than on overhead systems, and require more time to repair, therefore no system should be considered that cannot be sectionalized, and has not reasonable emergency facilities provided for restoring service with the least possible delay. It is advisable when installing secondary mains to make a loop service of the main instead of running the service direct; this permits the main to be sectionalized in case of trouble and reduces the number of consumers out of service. In three-phase work it is the usual practice to provide 3-core cables for the power mains and single-conductor cables for lighting mains, and to keep to as few sizes as possible regardless of the load, provided of course, that the voltage drop and ampere carrying-capacity are satisfactory.

Types of Distribution Cables. For underground distribution work the two-conductor concentric cable is used to a great extent as feeders for both direct-current and alternating current circuits. It possesses the advantage of not giving rise to any external magnetic field, since with equal currents flowing in opposite directions through the conductors, the magnetic effects, due to the two currents, neutralize each other at every point, and owing to the absence of external field there is no hysteresis or eddy currents set up in the cable sheath or near-by metal. The two-conductor type of cable is therefore highly recommended for alternating current circuits, but it has a disadvantage where taps to service mains become necessary.

The three-conductor concentric cable is mainly

used on single-phase (3-wire) distribution systems, and the outer conductor, which forms the neutral conductor, is generally of one-half the size of each of the inner conductors ; this type of cable is not recommended for use on three-phase circuits because of its inherent ability to produce unbalanced current due to electrostatic capacity in the cable. However, it has an advantage over the 3-core cable in that the effect of eddy currents in the cable sheath and armour is reduced to a negligible value.

The 3-core cable is best adapted for use on three-phase circuits due to its inherent electrostatic symmetry. For low-voltage distribution mains, especially those of the larger size, the single conductor cable is somewhat in favour because of its economy and facility in making service taps. However, when these taps are few, the 3-core for three-phase, 3-wire distribution, and the 4-core cable for three-phase, 4-wire distribution, are preferable because of the lower costs as compared with a number of single-conductor cables and ducts.

Single-conductor cables larger than 0·5 sq. in. are rarely used in alternating current work owing mainly to the effect of sheath currents, and it rarely occurs that such cables are loaded to exceed two-thirds their maximum current carrying capacity, under which conditions the sheath current may run up to about 10 per cent of the total current flowing through the conductor. This evil can be reduced by proper bonding and by introducing, where possible, multi-conductor cables in place of one large single-conductor cable. In circuits of any considerable length, neither single conductor paper-insulated lead-covered cable, nor any other single conductor lead-covered cable should be used on alternating current circuits, not only on account of the greater inductance of the single conductor cable (the conductors of which are bound to be much further apart), but also because of the transformer effect (eddy currents induced in

the lead sheath), particularly in large size single-conductor cables carrying heavy currents.*

Earthing. To safeguard equipment and station attendants, it is advisable to earth all metal frames of generators, transformer tanks, and other apparatus; all high-voltage switch mechanism; all metal switchgear and the switchboard frames; the cases of instruments, and the secondary circuits of instrument transformers; lightning arrester equipment, etc., where a failure of insulation or where contact between high and low-voltage conductors occurs there is danger to persons coming in contact with lamp sockets and other appliances, for if the low-voltage circuit is insulated from earth (or even accidentally earthed through a high resistance), there may exist between the low voltage circuit and the earth a difference of potential, the value of which may range anywhere up to full voltage of the high voltage circuit, depending upon the conditions of the contact between the two circuits involved. Even with the high voltage circuit thoroughly insulated at all points except the one where failure has occurred, the current flow to earth, due to electrostatic capacity, may be sufficient with a few miles of high voltage cable to be dangerous to both life and property. These dangers can be practically eliminated by connecting low voltage circuits and the metal frames of electrical machinery and apparatus to earth. If the resistance to flow of current is low enough, a dangerous voltage cannot exist between low voltage circuit and the earth.

Where low voltage circuits are fed from high voltage distributing circuits through step-down transformers, puncture of transformer insulation is sometimes caused by lightning. While improvements in transformer insulation, cable insulation, overhead

* For further information on cables see *Electric Cables*, by F. W. Main, uniform with this volume, 2s. 6d. net.

lines and their construction, lightning arresters, etc., have all reduced the possibility of danger to a great extent, complete protection is not yet obtainable. With a proper earth-connection practically all danger can be eliminated.

In the stations where earth connections may be called upon to carry very large currents, the resistance of these connections should be low, and may range (depending on the protection which is required) from almost negligible values to a maximum of 1 or 2 ohms. In low voltage work (secondary distribution), where protection is desired against accidental contact with high voltage circuits, the resistance of the earth connection may safely be several ohms higher than a satisfactory station earth. The prime consideration in the installation of safe earth connections should be the fact that the current-carrying capacity of the earthing device is sufficient at all times to prevent a dangerous potential difference between the earthed circuit or apparatus and the earth itself.

It is important that separate earths be provided for circuits of widely different voltages in the same station, and if lightning arresters are installed on these circuits of widely different voltages, it is highly desirable that the arrester-earths be kept entirely independent one from the other. To save expense it is sometimes recommended to install one earth wire to serve several different classes of apparatus, circuits, etc., such as a lightning arrester and a low voltage circuit. It is evident that in the event of a discharge of the lightning arrester a high potential difference is likely to exist between the earth end of the arrester and the earth itself. This difference of potential is impressed upon the low voltage circuit, and may be a danger to life and property. For this reason separate earth wires should, in general, be provided for all classes of apparatus, and more particularly for lightning arresters. Furthermore,

where a good earth connection such as a water pipe cannot be made, the arrester earth-connection should be spaced at least 6 ft. from the earth-connection serving a low voltage circuit. (*See* Regulations mentioned in Appendix.)

It is sometimes stated that earthing electrical systems to water pipes may cause electrolysis by stray currents from the earthed circuits or danger to persons who might have occasion to work on the water pipes. The danger due to electrolysis by alternating current is but a fraction of 1 per cent of the damage done by the same quantity (ampere-hours) of direct current. Danger to persons can easily be avoided by removing the earthed connection when work is to be done on the water pipes, replacing them when the work is completed; but where multiple earth connections are used (not recommended for direct current circuits because of the possibility of electrolytic effects) it is unnecessary to take this precaution.

A group of cast-iron pipes driven vertically in a bed of coke, as free from sulphur as possible, give a certain degree of protection. In making the earth connections between the smaller secondary wiring and the station earth-bus, it is common practice to run the earth wires through iron pipes. While this method safeguards the wires from mechanical injury, the iron pipe increases the self-induction of the earth circuit, and to avoid this, all such wires should make metallic contact with both ends of the iron pipe. In the case of small transformers and circuits of limited capacity, this method of earthing affords ample protection. As the kilowatt-capacity of the transformers and circuits increases, it is necessary to provide earth connections of lower resistance. The practical limit of decrease of resistance with driven pipes, or even buried plates, is soon reached, and for circuits of large capacity the most obvious solution is to use the water pipe system which offers a much lower resistance than driven pipes or buried plates.

CHAPTER III

SYSTEM OPERATION

THE tendency in electric power system design, more particularly in power station design, has been towards a more systematic and compact organization of the generating machinery and apparatus and the utmost simplification of the entire system consistent with the highest efficiency. The standard practice in modern power station engineering embodies: (i) Simplicity of design. (ii) Subdivision of the machinery, equipment and apparatus into sections so as to localize the effect of trouble. (iii) Provision for the systematic extension of the system to provide for future power requirements. In its simplest form the power station would consist of a boiler room, turbine or engine and generating room, and switchboard platform or gallery. In stations of large capacity, the boilers are frequently arranged in two tiers, or in groups, each group having its own chimney and flues, and independent systems of feed and steam piping. This arrangement of the station is generally referred to as the "unit system," the distinguishing feature of which is that the boilers, turbines or engines and generating and transforming apparatus are arranged in separate units or groups, each one of which embodies all the essential features of a complete generating plant. The great advantage of the unit system lies in the fact that trouble with any single piece of plant or apparatus is localized, so that its effect is felt mainly in the unit in which it arises.

In the design of a power system, the primary object in view is to deliver power at the busbars —preferably to the consumer—for the least expenditure of money, due importance being given to reliability of operation,

which should always be taken as the controlling principle. The fixed charges should be considered as carefully as the operating expenses. In the latter expenses, fuel is the most important item of cost, frequently amounting to more than all other operating costs combined, and the perfection of those details of design and management which will effect the greatest economy in the use of fuel will usually make the best return on the investment. The advanced state of the art of manufacturing steam units and generators, the increasing demand for electricity, and the greater care and vigilance exercised by the operating forces, all tend to decrease the consumption of fuel for a given power delivered.

Location. One of the greatest difficulties, particularly in this country, is to determine and acquire the most economical location of the generating station. In the selection of a power station site, a few of the essential factors involved are: Cost of the site; coal delivery facilities; available water for cooling, etc.; character of soil for foundations and cost of foundations; and the position of the centre of load of the system.

In large towns, where land is extremely valuable, or the available area limited, the amount of power which can be generated per unit of ground area occupied may be the controlling factor in deciding upon the power station site. Except in the very large towns, this condition rarely exists. After locating several available sites and determining the more desirable sites from physical and electrical standpoints, the values of the sites should be compared one with another, to determine which site is, on the whole, most advantageous.

The power station should be located near an ample supply of water for condensing purposes, in order to secure the advantages from the use of the most efficient types of steam apparatus. The location

should be convenient to a steam railroad or tide-water where coal can be received and handled with least expenditure of labour. The location of the nearest coalfields should be considered particularly in these days of high transport charges. The relative merits of coals from different coalfields should be considered in their bearing on boiler furnace efficiency, and as regards their calorific values.

When examining the sites available, the character of the soil should be investigated. Borings may become necessary to determine the disposition of the seams or strata. Generally, hard rock of sufficient depth affords the best sub-foundations, compact sand and coarse gravel come next in order of merit, and firm clay has a very good bearing power. If the soil conditions are poor and it is necessary to drive piles and build special foundations, the cost per unit of installation will be higher.

The electrical centre of gravity of the system is very important. If the direct current system be used, it is desirable to select a location as near as possible to the centre of gravity of the load, in order to reduce the investment in copper, but in the case of an alternating current distributing system, this is of less importance. The amount of copper required in the distribution system increases in proportion to the square of the distance of the power station from the centre of load, providing that a fixed voltage is maintained at the generating station and a predetermined full-load drop is allowed in the feeders and mains of the distributing system. In towns where the bulk of the supply is within the economical radius of distribution for direct current service, and where direct current generators form the larger part of the existing equipment, the common solution of the problem is to use this type of apparatus for the town supply, adding alternating current apparatus to supply the more distant portions of the system. At the present time alternating current generating

stations and distribution systems are regarded as the most efficient to install in the larger towns, where heavy traffic and industrial power is distributed over a very wide area, and where the interest on the investment in direct current feeders and the cost of their maintenance would amount to more than the corresponding charges plus the conversion losses in an alternating current system.

The location of a station may also decide the kind of distribution system to be employed, i.e. "ring," "radial," or "radial-group" system, the ring system generally having the advantage over the other two. Location, distance, and size of secondary and service mains are all related with the drop in voltage and consequent loss in revenue. For instance, a voltage drop of 2 per cent below normal lamp rating causes a loss in revenue of about 5 per cent as well as nearly 7 per cent loss in illumination.

System Cost Records.* The system of records and management of an electric power undertaking varies largely with the magnitude of the system, the class of production (steam, gas or hydraulic power), the kind and class of consumers, and the country, etc. A classification which covers most requirements divides the expenditure under the two main headings, Construction and Operation, each of which may be subdivided under the headings: Production of power, transmission, distribution, utilization, and commercial sections.

Construction Costs may be classified as—

(i) *Organization.* This includes the incorporation and issuing of securities; the registration of mortgages and placing the undertaking in readiness to do business; royalties, franchise and licence; taxes, legal expenses; fees paid to promoters; miscellaneous.

(ii) *Generating Station.* Land, station structure, steam and electrical plant and all apparatus and devices to generate

* For technical records *see* Chapter VI.

electricity and conduct it to the station switchboard. In a hydro-electric plant this would include many other items, such as the cost of diversion-dam, head works, conduit, forebay, penstock, land, etc. In the case of a gas-electric plant there would be the cost of gas-making apparatus and land for same.

(iii) *Transmission Lines*. This includes the cost of line conductor, insulators and conductors of every kind used on the transmission system. The cost of poles or towers, structures and insulator pins, braces, brackets and other support fixtures ; guys and other supports for holding the supports (towers, poles and structures) in position, and all labour expended in connection with the construction of the pole lines or structures for carrying the transmission system.* The cost of all material and labour, erection and putting in place of the telephone system. Cost of all material, labour and other expenses in connection with the building, erection and putting in place of patrol-houses or other structures built (or purchased) along the transmission line for the purpose of operating or maintaining such lines. All costs of purchase, condemnation or other methods of acquiring lands to be used for the purpose of locating transmission lines, patrol houses or other property relating to the transmission system.

(iv) *Substations*. This includes the cost of land which is devoted to the use of the substation, housing for the operators, workshops, etc. Such costs should include, when paid for or incurred by the purchaser on its own behalf, cost of registration of title, cost of examination of title, conveyancing and legal fees, taxes, etc., to date of transfer of title, liens upon titles acquired, also the cost of obtaining consents and payments for abetting damages. The cost of all buildings, structures and improvements used and useful as substation or appurtenant buildings thereof. This includes all machinery foundations and settings if designed as a permanent part of the building and independent of their use in connection with any particular unit of equipment. Cost of all substation apparatus and equipment, etc., including electrical equipment such as rotaries, motor-generators, synchronous motors, transformers, boosters, switchboards, etc., and all fixtures permanently or otherwise affixed to the substation structure. Miscellaneous. Storage batteries, etc.

(v) *Distribution System*. This includes the cost of underground and overhead conductor material (cables and wires), insulators and conductors of every nature and kind used on the distributing system. Also the cost of labour, material and all other expenses in the purchase, erection and putting in place of this part of the distributing system. The cost of meters used in determining the amount of electric energy delivered to the

* The word *transmission* as used here, is taken to mean the carrying of the current from the point of generation (or purchase) up to the beginning of the distribution system.

consumers to whom it is supplied. Cost of all subway and line transformers, lightning arresters, switches, etc., used in connection with the distributing system. The cost of all cable or wire or other conductors and apparatus, ducts, insulation, supports or other accessories for connecting the distribution feeders and mains with electrical apparatus and appliances necessary to deliver electricity to consumers' premises. The cost of all lands, easements and privileges or other expenses of any nature whatsoever incurred for the purpose of securing the way-leaves (right of way) for distributing circuits. Miscellaneous.

(vi) *General.* This includes the cost of engineering and supervision during the period of construction, with the salaries, fees and expenses of engineers, reports, etc. It also includes such items as taxes, interest, insurance, travelling, legal expenses, and all fixtures, etc., chargeable to the construction equipment, instruments and tools, repair shops, store rooms, laboratories and apparatus, coal storage facilities, etc.

OPERATION COSTS may be classified as—

(*a*) *Production.* This includes cost of generation by steam, by gas or hydraulic power, and of delivery to the station switchboard. Or, in the case of purchase of electric energy, the cost is at the point of delivery to the undertaking. The costs should include all electric energy produced or purchased for the undertaking by another undertaking or company under any joint agreement for the sharing of expense (upon the basis of relative amounts of benefit to the several participants or any other basis), inclusive of provision in such expense for depreciation of plant, but exclusive of allowance for profit or return upon the value of property used in such production, etc.

(*b*) *Transmission Lines.* The cost of all labour, supervision, material or other expense employed or used in the inspection, patrol and operation of the transmission system between the high tension switches at the point of generation and the substation, including the testing of the lines. The cost of all operating labour, supervision, operating supplies consumed and expenses incurred in connection with the operating of rotary and static substations. In fact all transmission operating expenses, including substation operation, but not maintenance charges of any kind.

(*bb*) *Transmission Lines* (*Maintenance*). The cost of all labour and materials incurred in making repairs to the transmission system, consisting of the cost of repairing and renewing towers or poles or underground cable ducts, insulators, insulator-pins, braces, brackets, and other fixtures, guys and supports for holding the towers or poles or other structures in position ; also repairs of towers and other structures maintained primarily for supporting the overhead transmission system ; also the repairing and renewing of conduits and cables, etc. The cost

of repairing substation buildings and permanent fixtures therein, including the land and adjacent streets, vaults, sheds, pits, permanent foundations of apparatus, etc. The cost of repairing apparatus and machinery in the substations, including rotaries, transformers, boosters, motor-generators, storage batteries, substation cables and wiring, switches, switchboards and instruments, etc. Cost of repairing the telephone system entire, and any other item of maintenance of the transmission system.

(c) *Distributing System.* This includes the cost of all material and supplies consumed and all expenses incurred in connection with the operating of service transformers, either on the premises of consumers, in underground chambers or on poles adjacent to or adjoining such premises, and all inspection of transformers and their replacement in the course of their periodical testing and inspection or damage. The cost of all labour employed in removing and resetting meters on the premises of consumers and placing meters; also testing and inspecting meters both on the premises of consumers and in the shops; also all supplies consumed and expenses incurred in connection with the operation of the Meter Department; the cost of tools used in this department, together with repairs upon the same. The cost of maps and records of the system, including the expenses and incidentals of persons making them; also the cost of supplies and expenses in the office of the engineer, and all other expenses of every nature whatsoever for the operation of the distribution system.

(cc) *Distribution System (Maintenance).* The cost of repairing and renewing cables, joint-boxes, man-holes, poles, insulator pins, cross-arms, braces, brackets and other pole fixtures, guys and other supports for holding the poles, towers and other structures in position; also repairs of towers and other structures maintained primarily for supporting the overhead distribution system; repairing and renewing insulators and overhead conductors of the distributing system; repairing and renewing troughing, bridges, conduits, pipes, and fittings of the underground distributing system. The cost of labour and material consumed in maintaining service transformers, including renewing oil, re-painting, re-winding, removal and replacing; also repairs of such switches, etc., as are the property of the undertaking in consumers' premises. Also cost of repairs and replacement and all other maintenance not mentioned above.

(d) *Utilization.* The cost of labour employed in trimming and inspecting municipal and public and private arc and incandescent lamps, including those on consumers' premises; also cost of all supplies such as carbons, globes and the cost of the first installation of incandescent lamps (including cartage and delivery expenses) unless the consumer is charged for the first installation or unless it is proper to charge such first installation to capital; also such matters as the charge for Municipal

Local Board, or other inspection certificate, and that portion of cost and expense of the engineering staff or of other departments engaged in technical work. The cost of renewal of incandescent lamps on consumers' premises (including cartage and delivery expense) and cost of photometering incandescent lamps. Cost of inspection of consumers' premises, including such matters as the charge for the above-mentioned Inspection Certificates, and that portion of the salaries and expenses of the engineering staff or other departments than the Distribution Department engaged in technical work. The cost of all utilization operation expenses of every nature whatsoever not properly chargeable to the above mentioned.

(*dd*) *Utilization* (*Maintenance*). The cost of all labour and all materials consumed in the repairing and the maintaining of lamps and fixtures. This includes the cost of renewing lamps and lamp equipment, repairing and renewing of lamps in the utility shop, readjusting lamps and lamp equipment, renewal of defective parts, renewal of switches and cut-outs, repairs and renewal of mast-arms, hangars, etc., replacement and renewals of lamp poles, painting of lamp poles, etc. The cost of all maintenance, labour and material furnished to consumers for inside work without special charge, including such matter as replacing or repairing wiring fixtures or electric appliances, etc., etc.

(*e*) *Commercial*. This includes all expenses incurred in selling electric power and products, in determining the amount of sales, in making collections and keeping account of collections, where same are not properly chargeable to promotion expenses. Total expenses of meter-readers, including their lamps and appliances. The expense of the collection bureau, including commissions, car-fares, delivering bills, etc. Such cost of Contract Department as is not assignable to the promotion office, including attention to bill questions. Cost of keeping the accounts of consumers, being a proportion of the salaries and expenses of general officer and assistants in charge of the Commercial Department having to do with consumers' accounts.

The promotion expense includes the salaries and wages of all employees whose services are devoted to the promotion and extension of the electric utility business, including canvassers, demonstrators, distributors of circulars and advertising material; also the cost of supplies used and expenses incurred for stationery, newspapers, advertising, exhibits and other similar expenses. Also all other commercial expenses not properly chargeable to any of the above.

(*f*) *General*. This takes account of the salaries and expenses of officers (President, Directors, Manager, Treasurer, and Secretary, etc.) whose jurisdiction extends to the entire system and whose services cannot be allocated satisfactorily to the several departments. It also includes the salaries, travelling and

incidental expenses of general office accountants, auditors, and others whose time is devoted to the carrying on of the business of the entire system and cannot be allocated satisfactorily to the several departments. It includes the cost of office supplies, office wages such as messengers, porters, janitors, etc.; repairs of rooms and furniture, etc. Expenses such as postage, telephones, telegraph, taxes, legal, insurance, interest, and expenses in holding directors' meetings, publishing of notices and reports, etc.

The earnings or income of the undertaking are usually subdivided under the two headings Municipal and Commercial, the scope of which is—

Municipal. Service for street arc lighting, street incandescent lighting, lighting buildings, and power supply for works.

Commercial. Lighting and power for residences and industries. Power for irrigation. Power for mining. Miscellaneous light and power sales. Installation and sales of material, lamps, motors, etc. Rents from land and buildings. Interest and dividends from investments, etc.

The total charges (construction and operation costs) referred to above may be defined as the sum of all the operating charges plus interest and *fair* profit on the investment, and classified under two headings, as—

(*a*) *Investment Costs.* This includes construction, taxes, interest, insurance, fair profits, depreciation, maintenance, etc.

(*b*) *Production Costs.* This includes operating cost, cost of delivery to consumer, traffic and transportation, commercial, general, etc.

It is not the intention of this text to cover the engineering side of power generation by coal, gas, and water.* The long series of component parts from the generator to the consumer of electrical energy offers ample scope for checking and recording of each respective part, decrease or increase in the consumption of coal, gas, or water, as the case may be. Of importance at the present time is the relative saving in labour. A certain electricity undertaking in

* For this, reference should be made to other volumes in this series, particularly to *Water Power Engineering*, by Fergusson; *Hydro-Electric Development*, by Meares; and *Modern Central Stations*, by Marshall.

America, which operates a large steam plant and a hydro-electric plant under the same management, and feeding into the same transmission system, finds that per 1,000 kW capacity it takes 13·5 men to run the steam plant and the coal mine tributary to it; but for the same capacity in the hydro-electric plant only 0·6 of one man is required. This relative expenditure of labour—84 to 1 in favour of the hydro-electric plant—is particularly worthy of notice under present-day conditions.

System Operation. The simplest system to operate is that of a single and independently operated power plant supplying electrical energy direct to the consumers. Next comes a single and independently operated power plant supplying electrical energy to one or more substations, which in turn supply electrical energy direct to the consumers. Of still greater importance is the system where two or more inter-connected power plants supply electrical energy to several inter-connected substations. Then there is the yet larger system in which very large electric power plants—gas, steam, and water-power—are tied together as one comprehensive network through high voltage overhead and underground transmission systems, numerous transformer and converter stations supplying energy direct to the consumers.

The operation of any system, large or small, should be with a view to obtaining the greatest economy of operation under normal conditions, together with the least disturbance and most rapid re-establishment of service in the event of any accident or trouble in the stations or on the transmission system. In the smaller systems the engineer-in-charge usually takes control of the situation. In the larger systems with two or more stations, the senior station engineer usually takes control of the situation and of the operators and the station men under their direction. In the very large systems present practice is to control all

operations from an independent central point. In such cases a *system-operating engineer* is appointed to direct the operation of all the power stations, substations, and cable and transmission lines; to control all apparatus and inter-connections for parallel or combined operation; and to deal with all interruptions, etc.*

Centralized Control by System-Operating Engineer. To control these larger systems, the system-operating engineer is so situated at a convenient point—preferably remote from the power-stations—that by means of a private telephone system he is connected with all the power stations, substations, etc., and can have direct and immediate communication with every station engineer, station operator, and switchboard operator on the system. Indirectly he can also communicate with all these stations through the public telephone service. He thus controls not only the entire electrical system, but he is also supposed to know that all the apparatus on the system is operating in the most economical manner, according to the rate of steam consumption of the separate stations, and that electric power is being produced in the most economical manner possible.

In these very large systems where system operation is controlled from one central point, the system-operating engineer has usually before him a diagrammatic layout of all the stations, substations, transmission and cable systems, showing electrical wiring of generators, transformers, converters, motor-generators, synchronous motors, frequency-changers, and all controlling switches, etc., in the stations and on the transmission systems. There are also the records of load curves and water rates taken over a long period, besides the daily load curves from each

* For information on the automatic electrical protection of a.c. systems, see *A.C. Protective Systems and Gear*, by J. Henderson and C. W. Marshall, uniform with this volume, 2s. 6d. net.

power station and each substation, which enable the controlling engineers to allow for the many factors governing economy in each station.

Before any power station, substation, cable or transmission circuit or transformer is taken out of service, authority must be obtained from the system-operating engineer in order to ensure that the plant remaining in service is sufficient to supply the existing demand or to provide for contingencies known only to him.

The clearing of repairs in the stations and on the transmission system is also controlled by the system-operating engineer, and before work is commenced on any circuit, with particular reference to transmission and cable circuits, the line foreman always reports personally to the station operators or charge-engineers at each end of the transmission circuit, even though one of the stations be completely cut off from the electric power supply while repairs are in progress. The man in charge of these repairs is thus temporarily under the direction of the system-operating engineer, and is temporarily in control of the circuit, and hence responsible for protection of himself and of men making the repairs until he reports* to the station operator or charge-engineer that the circuit is " clear." Before a transmission line is taken out for repairs (except in case of accident or emergency), arrangements are made with the system-operating engineer in order to avoid departmental and other inconvenience, and in order that men and materials may be got to the site. This applies equally to repairs in power stations and substations.

The main functions of the system operating engineer vary with the kind of system and with its magnitude, but his three chief duties are—

(*a*) Under normal conditions to direct the operation of the power stations, substations, transmission and cable lines, etc., to obtain maximum economy.

* See *Transmission Line Clearance Report,* p. 92.

(*b*) To maintain a sufficient and satisfactory supply of power at all times and under all circumstances.

(*c*) After interruptions, to restore power service in the minimum possible time.

It is only in the larger systems that centralized control becomes an economic necessity, but all the above specified operating conditions apply equally to those systems where a separate and independent system-operating engineer is not in control. In such cases the responsibility is generally taken by the chief operator located in the largest and most important power station.

The charge engineer in each power station is held personally responsible for having sufficient capacity of boilers, turbines, engines and auxiliary apparatus in readiness to carry the normal load as required. Under instructions from the system-operating engineer or the chief operator carrying on the unified system operations, he will also carry such additional load as may be required. In case of sudden accident to a unit, which must be promptly taken out of service, the change is reported immediately to the system-operating engineer. Where it is desired to take a unit out of service for repair, it is first reported to the system-operating engineer. He is always well informed as to the number of engines, turbines and generators, etc., in service, as also the number of boilers under steam and banked. With regard to the substations, the operators must have in service such transformers, rotary-converters, motor-generators, etc., as may be needed to carry the load. In general, no switch on the primary (high voltage) side is operated without instructions from the system-operating engineer, except in cases of sudden accident or trouble, and in that event the system-operating engineer is advised immediately of the change in the operating conditions. The operator is held responsible for having sufficient capacity of transformers, converters, or motor-generators, etc., in operation. He

must periodically advise the system-operating engineer as to the load carried, exactly as in the case of the power stations, and his instructions are somewhat similar as regards repairs in the substation.

In the diagrammatic layout of the whole system (in the system-operating engineer's office) the various switching operations are generally indicated by the insertion of coloured plugs, one colour indicating that the switch is closed while the other colour indicates that the switch is open and that the machine, apparatus or line under consideration is cut out of circuit. When the station operator is ordered to parallel another machine, the system-operating engineer plugs in the same circuit on his "mimic" or "dummy" system layout, so that, at all times, the latter indicates the actual electrical connections. Similarly, in the case of a transmission line—which may be operated independently or in parallel with another line—when the line is ordered to be disconnected and is actually disconnected by the operator, the system-operating engineer takes out the plug on his layout board, thus recording the actual electrical disconnection of the line.

Every case of trouble likely to affect the regular operation of the system, occurring in or reporting to the power stations or substations, are promptly passed on to the system operating engineer. A complete "log" record is kept by the station operators, as well as the system-operating engineer of every transaction, such as: Units paralleled or taken out of service, giving the time; loads transferred or carried; ordinary and accidental shutdowns; actual or probable causes of trouble; and so forth. The system-operating engineer, in communicating his orders, generally asks the operator to repeat the order. This practice reduces the risk of misunderstanding or mistake. His log-book should contain every order for the operation of switches, connection or disconnection of generators, transformers or lines,

etc. The scope of his responsibilities may extend as far as the banking of fires in the boilers and to the water supply from storage, or pondage in the case of hydro-electric plants.

Instructions to Linemen. In some cases the telephone wires are strung on the same towers or poles as the high tension power wires. Experience has shown that this practice may lead to two dangers: (i) the high tension power wires may make accidental contact with the telephone wires due to a break in the former, which are always topmost; (ii) currents induced in the telephone wires may reach a very high voltage. The usual instructions to linemen working on high tension lines are—

Never attempt to connect up your telephone to the telephone line or touch the telephone line wires unless you are thoroughly insulated from the ground.

Should you find it necessary to work on the line, first call up the operator at the nearest or the given substation or station, telling him where you are and what is the trouble.

Do not go near the power wires unless you have received definite instructions and information from the operator that the line is "dead."

Before ringing on the telephone line, take down your receiver and listen. In this way you do not interrupt conversation.

Immediately you have finished work, report to the operator what you have done and that you are clear of the line.

If doing a number of days' work on the line, use the above instructions upon going-on in the morning and reporting-off at any time you are clear of the line, especially when you are clear for the night.

Always attach an earth and short-circuiting wire to the power lines before doing any work upon them, and be sure to remove the wire or wires before reporting when you are clear of the line.

Be very careful not to leave any pieces of wire or other material hanging from the power or telephone wires when you have reported the line clear.

Earthing the Neutral. The Board of Trade Regulations in this country stipulate that the middle wire of every three-wire system shall be earthed at the generating station, and efficiently insulated over the rest of its length. If the earth connection at the

generating station be through an appreciable resistance, this earth shall be the only one on the main, which should be carefully insulated at all other points. Where 3-conductor concentric cables are used, the outer being the neutral, it is usual to earth the station end of the neutral, thoroughly maintaining its insulation at all other points.

The effect of earthing the neutral of a high voltage system will be different for the different kinds of systems; it may be an advantage in one and a disadvantage in another, depending on the different system conditions. In alternating current distribution systems the neutral point should always be earthed, for the reason that a distribution system which supplies electrical energy at low potentials, transformed from a comparatively high voltage system, is subject to the danger of excessive voltages impressed on the low voltage circuits due to accidental contact. While the number of instances of this character is almost negligible, the operating conditions demand absolute protection, hence the need for a proper earth connection on the low tension side, i.e. earthing of the neutral of the low tension circuits.

The effect of earthing through a resistance is different from the effect of earthing direct or "solid." Each case must be considered on its own merits. Some of the most important points involved in earthing are: (i) To avoid throwing full potential on other phases when an earth occurs on one phase; that is, a limiting of the voltage from a phase to earth; (ii) To enable relays to operate quickly, surely and selectively. (iii) To locate breakdowns quickly. (iv) To prevent arcing earths. (v) Possible reduction in cost of cables, transformers, line insulators, etc., due to limiting the voltage above earth to 57·7 per cent of the voltage between phases (in the three-phase star system). (vi) Possible reduction in cost of lightning arresters. (vii) Possibility of using the earth as a conductor in the event of one

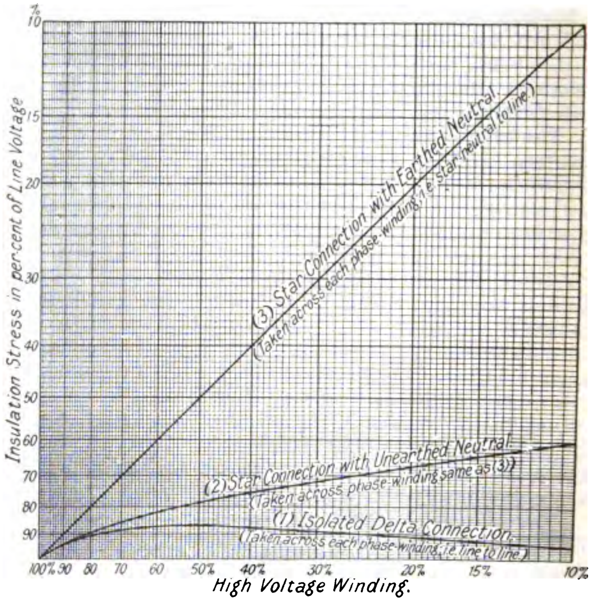


Fig. 7.—Effect of Earthing the Neutral of Three-phase Systems.

For legend of Fig. 7, see opposite.

The insulation stresses shown by these curves are from h.t. winding to earth at fundamental frequency *with one transformer terminal earthed.* The cases considered are for the stress in the insulation from winding to core, in per cent of normal line voltage, as follows—

(1) *Isolated delta.* The stress in the insulation is practically equal to line voltage at all points of the winding, the minimum being 86·6 per cent of line voltage at the middle of the phase winding.

(2) *Star with unearthed neutral.* The stress in the insulation decreases steadily (but not linearly) from 100 per cent of line voltage at the line end of the winding to 57·7 per cent (i.e. $100/\sqrt{3}$) of line voltage at the unearthed neutral.

(3) *Star with earthed neutral.* In this case the stress in the insulation decreases linearly from 100 per cent of line voltage at the line end of the winding to zero at the earthed neutral point.

In each case the curve gives the insulation stress in the winding of a phase not connected to the earthed line terminal assuming that the system is capable of maintaining line voltage when there is an earth short-circuit on one line.

			SYSTEM.		
			(1) Isolated delta.	(2) Star, neutral not earthed.	(3) Star, neutral earthed.
Insulation stress from h.t. winding to earth with one terminal earthed	Per cent of normal voltage stress.	Min. Max. Mean	86·6 100·0 93·3	57·7 100·0 78·8	Zero 100·0 50·0
	Factor of safety.	Min. Max. Mean	2·0 2·3 2·1	2·0 3·46 2·54	2·0 Infin. 4·0
Insulation margin with one terminal earthed.	Per cent of line voltage.	Min. Max.	100·0 113·0	100·0 142·3	100·0 200·0
Insulation margin or normal operation.	Per cent of line voltage.	Min. Max	142·3 171·0	142·3 200·0	142·3 200·0

This is based upon the standard voltage test, i.e. double the normal voltage or the equivalent of 200 per cent normal voltage across the winding.

line conductor being disabled, assuming the disabled wire is earthed at both ends or is disconnected and the line earthed at both ends (in the three-phase star system).

For an underground cable system it is preferable to earth the neutral through a resistance.

For an overhead transmission (through step-up transformers), the three outstanding points are : The system connection (star or delta); continuity of service with or without the earth ; relative danger to workmen with or without the earth. As regards electric supply direct from generators, it is advisable to earth the generator neutral in all cases, whether the supply is to a system of underground cables or to other distribution circuits.

The most important *advantages* of earthing the neutral in three-phase systems are—

(*a*) The average insulation factor of safety is greater than in isolated systems operating under similar conditions. (*See* Fig. 7.)

(*b*) The earthing of a conductor reduces the voltage of the system with respect to the earth.

(*c*) The voltage of fundamental frequency above earth is limited for any part of the circuit to $1/\sqrt{3}$, or 57·7 per cent of line potential when the neutral is earthed solidly at both receiving and generating ends of the circuit. A resistance inserted between neutral and earth increases the insulation stresses.

The *disadvantages* of operating with an *insulated* neutral in three-phase systems are—

(*a*) The average insulation factor of safety is less than in earthed systems operating under similar conditions. (*See* Fig. 7, pp. 64 and 65.)

(*b*) The potential stresses on the insulation at frequencies higher than fundamental frequency may, under certain conditions, rise so high as to injure or destroy apparatus connected to the system.

(*c*) An earth on the line is more likely to result in an arcing earth.

(*d*) An earth on the line increases the potential of the system with respect to earth.

An earth on a system with the neutral point earthed, results in a short-circuit, and a dynamic current flows, the value of which depends upon the combined impedance of the circuit through the earth and the impedance of the transmission circuit and apparatus through which the short-circuit flows. The worst short-circuit occurs when a "dead" earth happens on the circuit near the supply end where the neutral point is solidly earthed; this causes a complete breakdown of the short-circuited phase throughout the system, and the short-circuit current in this case is limited only by the impedance of the generators and transformers. To reduce the value of the short-circuit current, sometimes resistance is inserted between the neutral point and the earth. In designing the resistance elements, it is well to remember that the size of resistance will depend upon the time the short-circuit is maintained. Any resistance inserted in the neutral, if it is to limit currents to values appreciably less than those obtained when the neutral is "dead" earthed, must be capable of withstanding practically normal phase potential; practically all the voltage must be consumed by the resistance of the earth and the resistance of the neutral in series, to prevent undue rise in potential. A neutral will remain steady only when the $I_s R$ drop produced across the neutral resistance by the short-circuit current, I_s, is small compared with the line voltage. The neutral will remain fairly stable and not give rise to undue potential across the neutral resistance if the total resistance of the earthed line is not greater than about ten times the neutral resistance.

CHAPTER IV

SYSTEM FACTORS

Advantages of Centralization. System efficiency and economy are at their best when controlled by an exceptionally broad and sound engineering and commercial staff, and when the system as a whole is under the control of one general management. Centralization of system operations usually means a great saving in several directions, but mainly in the electric power stations due to: (i) The greater diversity of loads then served from the one system. (ii) A lowering of generating costs per kilowatt-hour due to improved power factor and load factor made possible by the general direction of all operations. (iii) A saving in cost due to centralization of management, engineering and general expenses. (iv) A decrease in the investment for such items as spare apparatus, machinery, equipment, etc. In other words, a number of small power stations under independent managements cause economic losses which can be avoided by centralization of power stations and concentration of management.

As regards the first cost per kilowatt of plant, it is evident that this depends upon a great many variables, such as the location of the station and its approach as regards economical transportation facilities by road and rail or water; cost of land and the character of the ground in its effect upon economical foundations, drainage, etc.; whether a number of small units or a few large units are installed; and whether labour-saving equipment is installed or not. The cost per kilowatt is further augmented in the case of a number of small units when we consider the amount of spare plant required for an equivalent kilowatt capacity. Also, independently operated plants require a greater spare capacity in plant, etc., than those systems in which power stations are operated

in parallel. Of still greater importance is the increased cost per kilowatt due to the operating charges which become proportionately less as the generating plants and network increase in size, as the quality of plants and network is improved, and as the efficiency of organization is increased. The larger systems always have the advantage, and as they become larger and more comprehensive, it is possible for them to obtain the benefit of the services of technical and commercial men of the broadest and highest ability, and also to keep a trained specialist at the head of every important section. The departmental specialists have each a single principal function in the organization, whereas, in a small power station, a general technical and commercial man is necessarily responsible for more functions than he can perform to best advantage. The larger systems are thus enabled to make great savings in other directions, such as elimination of mistakes in general, and all-round reduction in costs by the use of more efficient methods throughout.

System Factors. Some of the most important system factors deserving mention are: Power loss; voltage drop; average and maximum demand factors; diversity factor; load factor; operating load factor; capacity and plant factors; connected load factor; line loss factor; distribution loss factor; and power factor. These form the criteria of efficient installation and operation.

Loss Factor. Power loss and voltage drop are practically all included in line loss and distribution loss, and under ordinary conditions of operation the three main electric circuit properties are: resistance, reactance, and capacity.

Resistance depends upon the material of which the conductors are made, their sectional area, their length, and the temperature under which they are operating. Resistance itself is quite independent of the frequency, although there is a phenomenon dependent

on frequency known as *skin-effect*, which appears in very large conductors and to which is due an increase in the *effective resistance* of such conductors. The effect of resistance is to produce a drop of voltage *and* a loss of power.

Reactance is due to the alternating current field set up around the conductors by the current flowing in them. It is a quantity similar to resistance in that the product of the reactance by the current gives the reactance volts electro-magnetically generated by the current, just as the product of resistance and current gives the voltage drop due to the resistance; in other words, reactance is a voltage drop per ampere, and is expressed in ohms, and the reactance voltage drop is IX, expressed in volts. It differs from the resistance in that it is directly proportional to the frequency of the current. Its effect is to produce a voltage drop but *not* a loss of power.

For a simple estimation of power loss, let P represent the power to be delivered at voltage E; and let R and Z respectively represent the resistance and impedance of the circuit. Then current flowing through the circuit is P/E, and the loss is—

$$I^2R = \frac{P^2}{E^2} R$$

In terms of voltage drop e, the power loss is eI; and in terms of impedance it is I^2Z. For a single-phase circuit it is $I^2Z \cos \varphi$. For a three-phase circuit it is $\sqrt{3}\, I^2Z \cos \varphi$. The impedance per conductor is $e/2I$ for a single-phase circuit, and $e/I\sqrt{3}$ for a three-phase circuit (*see* Table IV, p. 35).

The current consumed by a given load is proportional to the voltage delivered, and since the power consumed by the load is proportional to the value EI, it is proportional to the square of the voltage. In alternating current work, the voltage drop is dependent both upon the impedance-voltage and the power factor. Thus, knowing the receiver voltage

E_r, the voltage at the generating station (neglecting line-capacity) is approximately—

$$E_g = \sqrt{(E_r \cos \varphi + IR)^2 + (E_r \sin \varphi + IX)^2}$$

(*see also* p. 23). The voltage regulation is—

$$e = 100 \; (E_g - E_r)/E_r$$

and the power factor at the generating station is—

$$(E_r \cos \varphi_r + IR)/E_g$$

In general, the limiting loss factor is either the power loss or the voltage drop. Fig. 8 is based on resistance-volt drop. The power loss must not be excessive and must not cause overheating, and the voltage drop must be kept within permissible limits in order that the regulation will be commercially good. For short distances the limiting loss factor may be the safe current-carrying capacity. For long distances and consequent high voltages the limiting factors may be regulation, power loss or mechanical strength of the conductor. In such circuits (overhead or underground, especially the latter) capacity is introduced by the electrostatic field surrounding the conductors, and this causes the so-called *charging current* to flow in the circuit (*see* p. 25). This charging current affects both the voltage regulation and the power loss, and in the higher altitudes it produces another loss called corona loss.

The *line loss factor* is usually taken as the ratio of the actual power loss (I^2R) during a year to the power loss that would have occurred if the line had carried continuously the maximum load imposed on the line during the year.

The *distribution-loss factor* is usually spoken of as representing the number of kilowatt-hours loss divided by the number of kilowatt-hours delivered. In this case the kilowatt-hours loss can be taken as the loss factor multiplied by the number of kilowatt-hours actually delivered.

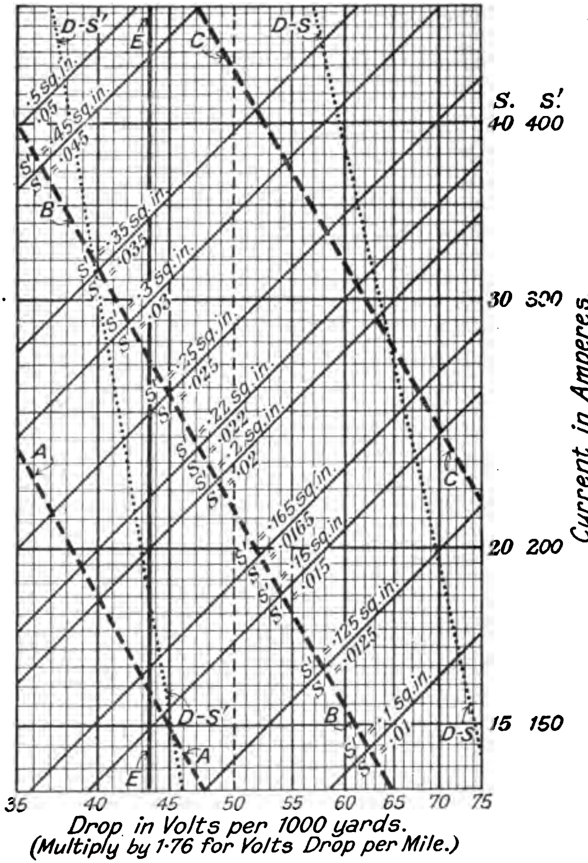


FIG. 8.—VOLTAGE DROP PER 1,000 YDS. OF THREE-PHASE CIRCUIT FOR DIFFERENT SIZES OF COPPER CONDUCTOR AND VARIOUS CURRENT VALUES.

For legend of Fig 8, see opposite.

S = for current from 15 to 45 A.
S' = for currents from 150 to 450 A.

NOTE.—The S lines can be used only with the S scale of current and the S cable sizes. Similarly the S' lines can be used only with the S' scale of current and the S' cable sizes.

Line.	*Represents Safe Current Density in—*
A.	Single-core cable, rubber insulation.
B.	Three-core cable, paper insulation.
C.	Single-core cable, paper insulation.
D.	Institute of Electrical Engineers' limit.
E.	Current density 1,000 A per sq. in.

EXAMPLES OF THE USE OF FIG. 8 TO DETERMINE VOLTAGE DROP

(1) *A three-phase cable,* 1 *mile long, with* 0·2 *sq. in. copper conductors transmits* 200 *A. What is the voltage drop?*

Using current scale S', proceed horizontally until the line $S' - 0{\cdot}2$ is reached. Then project vertically on to the bottom scale and read 43·4 V per 1,000 yds., which is $43{\cdot}4 \times 1{\cdot}76 = 76{\cdot}3$ V per mile. The voltage drop required is thus 76·3 V.

Projecting vertically from the point on the $S' - 0{\cdot}2$ line until the curve B is reached, it is found that this intersection lies between $S' - 0{\cdot}25$ and $S' - 0{\cdot}3$, i.e. for safe current density and the same voltage drop a conductor between 0·25 and 0·3 sq. in. should be employed.

(2) *A three-phase circuit,* 1,000 *yds. long, consisting of three single-core paper insulated cables with* 0·15 *sq. in. copper conductors transmits* 240 *A. What is the voltage drop?*

Using current scale S' and proceeding as before, the voltage drop is seen to be 70 V per 1,000 yds. Also, this size of conductor is then being operated at practically the limiting safe current density (curve C) for the type of cable employed. The chart shows that a slightly larger conductor is desirable.

(3) *A three-phase circuit,* 1,000 *yds. long, consisting of three single-core paper insulated cables with* 0·02 *sq. in. copper conductors transmits* 29 A. *What is the voltage drop, and does the proposal conform to the I.E.E. limit?*

In this case, current scale S must be used. The intersection between the line through 29 A on this scale and the line $S - 0{\cdot}02$ shows that the voltage drop is 63 V per 1,000 yds. The intersection is nearly on the I.E.E. limit line $D - S$, and is on the safe side of the latter, i.e. slightly more than 29 A can be carried.

(4) *A three-phase circuit,* 1,000 *yds. long, consisting of three single-core paper insulated cables with* 0.20 *sq. in. copper conductors, transmits* 200 A. *What is the voltage drop and does the proposal conform to the I.E.E. limit?*

Using current scale S' and the line $S' - 0{\cdot}2$, it is seen that the voltage drop is 43·4 V. The intersection is exactly on line E (current density 1,000 A per sq. in.), but is slightly above the I.E.E. limit curve.

The power losses on a given feeder or line may be different each month in the year, being less during the summer months than during the winter months.

Maximum Demand. In the year 1883 Dr. Hopkinson suggested the use of maximum demand as a factor determining the cost of electrical energy, and in the year 1892 he elaborated his previous ideas and showed that the maximum demand, in addition to the number of kilowatt-hours used, is absolutely essential in arriving at the proper cost of supplying electric energy. It is now generally recognized that any rate for electrical service must, in some manner, recognize maximum demand as well as the total amount of current or energy used. The demand may be expressed in kilowatts, kilovolt-amperes, amperes, or other suitable units. In other words, systems of charging for electric service may be based on the maximum demand either in the form of direct charge for power, direct charge for energy, or both, or on the load factor distributed over a period of time. By having the demand based on the kilovolt-amperes in place of kilowatts, the consumer has a material interest in keeping the power factor as near to unity as possible, which is a direct benefit to the electric supply company.

There are several *definitions for maximum demand* which introduce the element of time, namely: (i) The root-mean-square value of the load taken between two ordinates of time so placed that it will be a maximum. (ii) The constant load in kilowatts which, if continued for a length of time equal to the time interval, will give the same total value in kilowatt-hours as the actual load during the time interval, the interval being so chosen that the integral is a maximum. (iii) The greatest of all the demands which have occurred during a given period.

The *average demand* is the load which is drawn from the source of supply averaged over a suitable and

specified interval of time. The *maximum demand-factor* is a numerical factor, viz., the ratio of the maximum demand of any system or part of a system, to the total connected load of the system, or of part of the system under consideration. These definitions may be written—

(1) Average demand, in kW

$$= \frac{\text{Kilowatt-hours during period}}{\text{Hours in period}}$$

The number of kilowatt-hours consumed during the selected period of time is equal to the average kilowatt-hours demand multiplied by the hours in the period.

(2) Maximum demand factor

$$= \frac{\text{Maximum demand, in kW}}{\text{Connected load, in kW}}$$

The demand factor is usually required in determining the capacity and cost of the apparatus, etc., required to serve a given load.

We may also write—

Group maximum demand factor

$$= \frac{\text{Max. of the resultant curve combining all the individual maximums}}{\text{Connected load}}$$

Individual maximum demand factor

$$= \frac{\text{Individual maximum demand}}{\text{Connected load}}$$

$$\text{Peak demand factor} = \frac{\text{Peak maximum demand*}}{\text{Group maximum demand}}$$

$$\text{Peak maximum demand} = \text{Group maximum demand} \times \text{Peak demand factor.}$$

Diversity of Demand. Where system supplies a number of consumers, the individual loads do not rise and fall simultaneously. There is a certain

* Occurring during the peak on the system probably between 5 p.m. and 6 p.m.

amount of over-lapping between the individual loads and, according to the extent of this overlapping, the maximum demand on the power station is a greater or less fraction of the sum of the individual maximum demands. The fixed charges which should be carried by each consumer are lower, the less the overlapping between individual load curves. The diversity of two or more peaks may be partial or complete. Diversity may also occur on account of either yearly or daily fluctuations in the time that the maximum of a given load occurs.

The investment required in the various parts of a system for each kilowatt of maximum demand, determines the fixed charges which must be considered in determining costs. The existence of a diversity factor between the demands of a large number of consumers permits their demands to be supplied with a much less investment in generating capacity, and at a lower cost of production than would be possible if the same consumers were operating individual power plants. The investment cost is further reduced by the ability to use large generating units, which cost much less per kilowatt than the smaller sizes used in isolated plants.

The usual *definition of diversity factor* is that it equals the ratio of the sum of the maximum power demands of the subdivisions of any system (or parts of a system) to the maximum demand of the whole system (or of the part of the system under consideration), measured at the point of supply; or, the ratio of the sum of the individual maximum demands of the number of loads during a specified period to the simultaneous maximum demand of all these same loads during the same period. Diversity of demand implies that the maximum demands of the various consumers of the different classes and character of loads and of the different conditions in a system, do not occur at the same time, i.e. the individual maximum demands are not coincident.

From the formula—

Diversity factor

$$= \frac{\text{Arithmetical sum of all the individual maximum demands}}{\text{Maximum simultaneous demand (ascertained from combined load curve).}}$$

it will be seen (i) That the arithmetical sum of all the individual maximums is equal to the maximum of the resultant load curve multiplied by the diversity factor. (ii) That the diversity factor makes the maximum demand imposed on the generating station only a fraction of the arithmetical sum of the maximum demands of all its customers. By serving the customers from the same transmission system a saving is made in the power station equipment owing to the diversity of the different loads.

Where two or more power plants are concerned the diversity factor is the ratio of the sum of the maximum peak loads of separate plants which would serve the individual communities to the maximum peak load that would occur if the plants were combined.

This may be illustrated by a consideration of the load curves of three generating stations, showing—

No. 1 *Plant.* Commercial power and lighting load together with the local tramway service ; maximum output, 1,300 kW.

No. 2 *Plant.* Power and lighting service ; maximum load, 800 kW.

No. 3 *Plant.* Mostly residential and business lighting; maximum output, 850 kW.

Plant No.	Max. individual peaks during the year.		Largest coincident peak during the year.	
	Kilowatts.	Time.	Kilowatts.	Time.
1	1,300	8.20 a.m.	1,240	5 p.m.
2	800	5 p.m.	740	
3	850	8 p.m.	600	
Total	2,950	—	2,580	—

Diversity factor = 2,950/2,580 = 1·14

showing a difference of 370 kW between the largest coincident peak and the sum of the maximum peaks.

The diversity factor in two or more towns may be quite variable, and in some cases it may be large, while in others it may be relatively small. In some cases it has been found that when a local supply system is substituted by a large power distribution system, the diversity factor decreases (notwithstanding the enlargement of the system), due to the class and the amount of power business. No matter what the system—unified or independently operated—there is intermittent work and consequently a diversity factor, and the conditions determining the time of the peak load must vary considerably in different places, due to: Different classes of industries and consumers; local weather conditions; latitude, longitude and altitude, etc.

Load Factor. Load factor has an important effect on the cost of producing power. A low load factor involves the use of relatively large plant operating at light and inefficient loads; but with a high load factor, all the elements of expense that enter into the production of power are at a minimum. The total cost of management and operation is practically constant and independent of the load factor, but the cost per kilowatt-hour net output decreases as the load factor increases. The total cost of coal varies with the load factor, but not quite so rapidly, whereas the cost of coal per kilowatt-hour net output increases with a decreasing load factor. The total kilowatt-hour net output, and the turbine- (or engine-) and active-fire hours vary directly with the load factor. The banked-fire hours increase with a decrease in load factor, but not quite so rapidly. A great many variables enter into hydro-electric systems, which may or may not be operated in parallel with steam-electric plants, and which may or may not have sufficient storage to permit the delivery of their full share of energy at any commercial load factor, that is, with constant energy output and not constant power output.

There still exists some confusion as to the exact *definition of load factor.* Col. Crompton, in the year 1891, defined load factor as the ratio of the actual kilowatt-hours generated during the year to the product of the maximum load of the year and the total hours of the year (8,760 hours). The confusion among a number of central station men is due to failure to distinguish between *maximum load* and *plant capacity or station capacity* and *total machine rating.* Load factor should undoubtedly be based upon the *maximum load.* Plant capacity and machine rating are taken into consideration in the "plant factor" and "capacity factor" mentioned on page 81.

Load factor may be referred to any period of time, and is defined as the ratio of the actual net output during that period, to the net maximum load* multiplied by the total hours in the period. Thus, the *annual load factor*, or the load factor for the year, is the ratio of the number of kilowatt-hours generated, to the maximum demand times the number of hours in 1 year. Thus—

Annual load factor, in per cent

$$= \frac{\text{Kilowatt-hours generated per year} \times 100}{\text{Maximum demand of the year} \times 8{,}760}$$

The term "kilowatt-hours output" or "kilowatt-hours generated" may mean the energy delivered at the station switchboard or it may mean the amount delivered at the substation, these two interpretations clearly being different.

A *simplified definition of load factor* is—

$$\text{Load factor} = \frac{\text{Average load during period}}{\text{Maximum load during period}}$$

or

$$= \frac{\text{Kilowatt-hours expended during period}}{\text{Maximum load} \times \text{Hours in period}}$$

* Usually for a 1-hour period.

Hence, the average output is equal to the load factor multiplied by the maximum power; or the number of kilowatt-hours expended during a period is the average power multiplied by the number of hours in the period considered.

Daily load factor is referred to a period of twenty-four hours, and may be expressed as follows for supply station and consumers respectively—

$$\text{Station daily load factor, per cent} = \frac{\text{Net kilowatt-hours output per 24 hrs.}}{\text{Net max. hour's load (kW)} \times 24} \times 100$$

$$\text{Individual consumer's daily load factor, per cent} = \frac{\text{Kilowatt-hours consumed per 24 hrs.}}{\text{Max. demand (kW)} \times 24} \times 100$$

$$\text{Group of consumers' daily load factor, per cent} = \frac{\text{Total kilowatt-hours consumed per 24 hrs.}}{\text{Group max. demand (kW)} \times 24} \times 100$$

The "*operating*" *load factor* may be taken as the ratio of the average hourly load for the year to the maximum power demand during the year, or, the average load during a certain period of time, such as a day, a month, or a year, during which the plant operates, to the maximum demand within that period.

The *average power load* referred to above may be taken over a period of time such as a day, a month, or a year, the *maximum load* being taken as the average over a short interval of the maximum load within that period. *In each case, the interval of maximum load and the period over which the average is taken should be specified.* The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be taken.

The Standardization Rules of the American Institute of Electrical Engineers define load factor as the "ratio of the average power to the maximum power during a certain period of time." This is

defined as the load factor of a system, plant or machine, as the case may be.

On the other hand, the National Electric Light Association (U.S.A.) defines load factor as "the actual power consumed per annum divided by the product of the installed rated capacity times 8,760 hours of the year." As will be appreciated from the preceding paragraphs, these two definitions may give very different results.

The rate curve in Fig. 9 shows the price in pounds (£) per h.p.-year corresponding to any rate in pence per kWh and any load factor up to 100 per cent.

Station or Plant Factor. Load factor and "plant" or "station" factor are frequently confused. Load factor, as explained above, is the ratio of the average load to the maximum demand, and not to the installed capacity of the plant, which is only a part of the system. The *plant factor* is the load factor based on the rated capacity of the plant. It is defined as the ratio of the average load to the rated capacity of the power plant, i.e. to the aggregate rating of the generators installed. It is expressed by—

$$\text{Plant factor} = \frac{\text{Average hourly load for the year}}{\text{Aggregate rated capacity of the generators } \textit{installed}.}$$

Hence, the average load for the year is the aggregate rated capacity of generators installed multiplied by the plant factor. In a like manner we may write—

$$\text{Capacity factor} = \frac{\text{Average hourly load for the year}}{\text{Aggregate rated capacity of the generators } \textit{supplying the load}.}$$

An alternative expression for the capacity factor is—

$$\frac{\text{Output (net) in kWh} \times 100}{\text{Generator capacity running} \times \text{machine hours}}$$

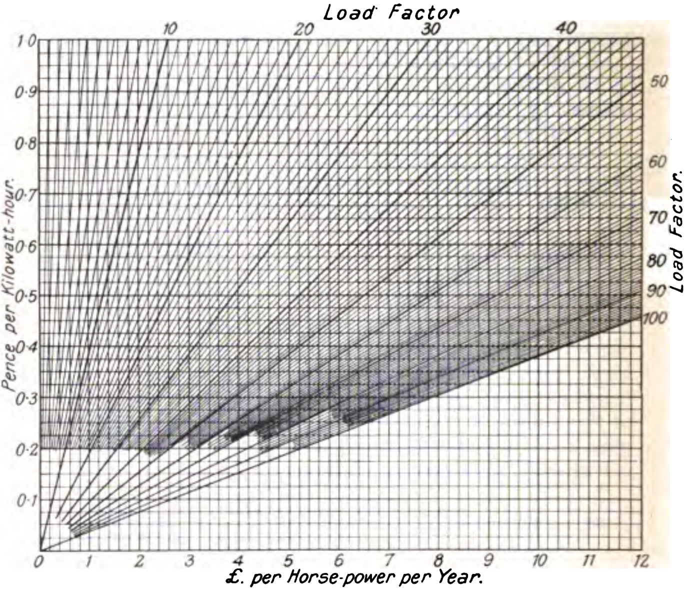


FIG. 9.—CHART FOR RATE DETERMINATION PER H.P.-YEAR CORRESPONDING TO ANY LOAD FACTOR AND ANY PRICE PER KILOWATT-HOUR.

For rates up to 1d. per kWh the chart is read directly. Thus 0·5d. per kWh at 35 per cent load factor corresponds to £4 12s. per h.p.-yr. For higher prices per unit, the chart is used proportionately. Thus 1·5d. per kWh at 35 per cent load factor corresponds to 3 × £4 12s. or £13 16s. per h.p.-yr.

Connected Load (Factor). This is defined as the combined continuous rating of all the receiving apparatus on consumers' premises, connected to the system, or part of the system under consideration. It is expressed by—

Connected load (factor) = Sum of the rated loads.

More often it is taken as the *ratio of the average power to the connected load.* It may also be expressed in terms of the product of the load factor and the demand factor.

Reliability (Factor). This factor takes into account the spare plant, apparatus and equipment required to ensure continuous service. The charges on this spare plant, etc., have quite an effect on the cost of power in a central station system where reliability must be one of the main considerations.

Power Factor.* Since the electricity sold is generally measured in kilowatts, any decrease in power factor lowers the effective or commercial capacity of the generator, and this reduction in capacity extends to the prime movers. In a steam-generating station it extends also to the auxiliaries, such as boilers, condensers, pumps, etc., in all of which a very considerable portion of the total investment is rendered idle if the system operates at low power factor. On the other hand, it is the recognized practice of all manufacturers to rate the capacity of generators and power transformers in kilovolt-amperes, not kilowatts. The effect of power factor on power transformers, although smaller in magnitude than the generators, must be considered, since it occurs twice in high voltage systems, i.e. in the step-up and in the step-down transformers.

* For a full treatment of power factor and its correction see *Power Factor Correction,* by A. E. Clayton, uniform with this volume, 2s. 6d. net.

The power factor of an alternating current system is taken as the ratio of the actual kilowatts to the apparent kilowatts or kilovolt-amperes flowing in the system, i.e.—

Power factor = Kilowatts/Kilovolt-amperes

The apparent kilowatts are the product of the volts and equivalent single-phase amperes as shown by the voltmeter and the ammeter respectively, while the actual kilowatts are those shown by a wattmeter. The kilovolt-amperes are the product of the volts by the resultant of two currents, one of which is the power component and is in time-phase with the voltage, whilst the other is the wattless component which leads or lags behind the voltage by 90 electrical time-degrees.

The *wattless factor* may be defined as the factor which, multiplied by the product of volts and amperes, will give the wattless component of kilovolt-amperes supplied. Its value is sin φ, where φ = angle of lag or lead of current with regard to voltage, and cos φ = power factor. The sum of the squares of the power factor and wattless factor is equal to unity, i.e.—

$$\text{Cos}^2 \varphi + \sin^2 \varphi = 1 \cdot 0$$

Similarly, power factor may be defined as the ratio of true power to the square root of the sum of the squares of the true power and the reactive power, i.e.—

$$\text{Cos}\, \varphi = \frac{P}{\sqrt{(P^2 + Q^2)}}$$

where P = algebraic sum of the true (or power) watts.
Q = algebraic sum of the reactive watts in all of the component parts of the circuit.

This expression is that of a ratio between the amount of power actually delivered in a circuit and the amount of power which might be delivered without exceeding the same heating loss.

A more exact definition of power factor takes into

account two distinct conditions: (i) Phase displacement between current and voltage. (ii) Inequality in the magnitude of the currents in the several phases. Allowance should also be made for two distinct items in the cost for power: (i) The fixed charges on the additional transmission and generating capacity required to supply the load at less than unity power factor. (ii) The cost of the additional power loss in the system or circuit under consideration; the current for inductive load is proportional to $I = i/\cos\varphi$, i.e. the lower the power factor, the greater the current and therefore the higher the heating loss. It therefore seems that the more logical and economic definition of power factor can be taken as the ratio of the actual power to the power which might be supplied to a load either by the same generator capacity or with the same power loss.

CHAPTER V

SYSTEM RECORDS

PRACTICAL and reliable records of the operation of plant, apparatus and equipment in stations, records of transmission line operation, and records of the distributive system, are most valuable. They serve as an education to operators and attendants by keeping them into closer touch with the essential details. Moreover, they give information showing where possible economy can be made and plant efficiency improved. In the upkeep of records it is desirable that, within reason, all those details which affect the economy, efficiency, and reliability of the system be recorded and filed, and that operators and their assistants be instructed in the preparation and intelligent utilization of such records.

Different systems employ different methods, but it is usual to have : (i) Loose-leaf records of the operation of station plant, etc. (ii) Card index records of transformers, towers, poles and other structures, lightning arresters, motors, meters, etc. (iii) Maps of system extensions with records on cards. (iv) Map records of removals of transformers, cables, and other circuits, etc., with records on cards showing reason for removal and whether they are going in stock, in the repair shop, or into other service. (v) Map records showing location of, and load on the transformers, etc. (vi) Map records showing location of lightning arresters, etc. (vii) General map record of all stations, distribution transformers, cables, lines, lightning arresters, sectionalizing and interconnection switches, etc.

Construction costs are reduced by a careful recording of details, by simplicity in design, and by the use of a few large units in place of many small units.

Operating costs are reduced by recording details of combustion, keeping reliable records of banked fires and actual fire-hours showing their proper relation, and when it is profitable to let the fires out; by records of average load on the prime movers; and by the use of highly efficient apparatus.

The specimen record forms on pp. 88–100 relate to the principal departments of an electric power system. Many more forms are required for the keeping of complete records, but those given are the most important ones. These forms show clearly the principal factors governing the efficient operation of power systems, and also demonstrate the potential value of properly-kept records.

It may be emphasized that good judgment must be exercised in selecting the data to be recorded, and that the records themselves are but a means to an end. It is not sufficient merely to make and file the records—they must be studied carefully and regularly, and the information which they yield must be applied to the improving of efficiency, using this word in its widest sense.

GENERATING STATION DAILY REPORTS

SWITCHBOARD REPORT

WEATHER TEMP.

DATE

Time	D. C. GENERATORS.					ROTARIES				A. C. GENERATORS								Total A. C. & D. C. Kilowatts	A. C. FEEDERS								
	No. 1	No. 2	No. 3	W M. 1 2 3		No. 1		No. 2		No. 4	No. 5	No. 6	No. 7	W. M. No. 1		W. M. No. 2			1	2	3	4	5	6	7	8	9
	A	A	A	W. M. Reading	K. W.	W. M. Reading	K W.	W M. Reading	K. W.	K. W.	A.	A.	A.	W. M. Reading	K.W.	W. M. Reading	K.W.		A	A	A	A	A	A	A	A	A
12																											
1																											
2																											
3																											
4																											
5																											
6																											
7																											
8																											
9																											
10																											
11																											

BOILER ROOM LOG

FIRST WATCH Date________

Boiler	Operation	First Watch 12 M. to 8 A.M. 12	1	2	3	4	5	6	7
No. 1	Fires Cleaned								
	Tubes Dusted								
	Blown Down								
	Banked								
No. 2	Fires Cleaned								
	Tubes Dusted								
	Blown Down								
	Banked								
No. 3	Fires Cleaned								
	Tubes Dusted								
	Blown Down								
	Banked								
No. 4	Fires Cleaned								
	Tubes Dusted								
	Blown Down								
	Banked								
No. 5	Fires Cleaned								
	Tubes Dusted								
	Blown Down								
	Banked								
No. 6	Fires Cleaned								
	Tubes Dusted								
	Blown Down								
	Banked								
Blower No. 1									
Blower No. 2									

Meter Readings: Meter	Beginning Watch	Ending Watch	Difference	Result
Coal Scales No. 1				
Coal Scales No. 2				
Stoker Counter No. 1				
Stoker Counter No. 2				
Stoker Counter No. 3				
Stoker Counter No. 4				
Stoker Counter No. 5				
Stoker Counter No. 6				
Boiler Feed Water				

Total Coal __________ Lbs Total Water __________ Lbs

Stokers	
Sign	Watch Engineer
	Stoker in Charge
Note	Draw a line for boilers under fire ⟵⟶
	Make a check V against time fires are cleaned
	Make a cross X against time tubes are dusted down
	Make a circle O against time boilers are blown down
	Draw a line for banked boilers ⟵⟶
	Draw a line for blower running ⟵⟶

GENERATING STATION DAILY SUMMARIES.

DATE____________

SUMMARY

MACHINE OR BUS	BUS No. 1	BUS No. 2	BUS No. 3	GENS. 1, 2, 3	ROT. No. 1	ROT. No. 2
Meter Number .						
Reading Midnight To-day . .						
Reading Midnight Yesterday .						
K.W.Hrs. for To-day . . .						

A.C. Generated = A = ____________ K.W. Hrs.
D.C. Generated = D = ____________ K.W. Hrs.
Total Generated (A + D) = T = ____________ K.W. Hrs.
Maximum Peak Load ____________ K.W.
Average Load ____________ K.W.
Load Factor ____________ %

DATE____________

SUMMARY OF DAILY OPERATING REPORT

Total K.W. Hrs. Generated . . . ____________
K.W. Hrs. Railway . . . . ____________
K.W. Hrs. Lighting & Power . . ____________
K.W. Hrs. Station Auxiliaries . . ____________
Lbs. Water Evaporated . . . ____________
Lbs. Coal Used . . . . . ____________
Value Water Used . . . . ____________
Value Coal Consumed . . . . ____________
Value Oil Consumed . . . . ____________
Labour Cost . . . . . ____________

Total . . . . ____________

Lbs. Coal Per K.W. Hr. . . . ____________
Lbs. Water Per K.W. Hr. . . . ____________
Lbs. Water Per Lb. Coal . . . ____________

K.W. Hr. Cost . . . . . ____________

REMARKS—

SUBSTATION DAILY REPORT

Date ____________

Time	Temperature							Incoming Line	Rotary No. 1				Total	D. C. Feeders									
	Room	No. 1 Trans.	No. 2 Trans.	No. 3 Trans.	No. 4 Trans.	No. 5 Trans.	No. 6 Trans.	Voltage	Load	Wattless Comp.	Watthour Meter		Total	Totalizing Watthour Meter		1	2	3	4	5	6	7	Voltage
	°F	°F	°F	°F	°F	°F	°F	K. V.	Amps. A. C.	K. W.	Meter Rdg.	K. W.	Kilo Watts A. C.	Meter Rdg.	K. W.	A	A	A	A	A	A	A	V
12																							
1																							
2																							
11																							
12																							
1																							
11																							
12																							

SUMMARY

Watthour Meters	Rotary No. 1	Totalizing D. C. Meter	Station Service Meter
Reading Midnight To-day			
Reading Midnight Yesterday			
K. W. H. for To-day			

OPERATORS

12 to 8 ____________

8 to 4 ____________

4 to 12 ____________

Interruptions: Breakers Out: Unusual Occurrences, Etc. ____________

Total Station Input ____________

Total Station Output ____________

Conversion Loss ____________

Peak Load ____________

Average Load ____________

Load Factor ____________

OPERATING DEPT. TRANSMISSION LINES.

To Operator at.. **Date**..............................**from 12m. to 12m.**

LINEMEN ARE WORKING ON MAIN CIRCUITS AT THE FOLLOWING PATROLS:

Patrol No.	10				12				14				16				18				20				22			
Circuit No.	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Indicate by x																												
Tower No.																												
Commencing																												
Completing																												
Reported Clear by																												

DO NOT THROW ON CURRENT UNLESS YOU HAVE CLEARANCE FROM EACH PATROL INDICATED

Remarks:

Current ordered on at..............................**by**..............................**Sig. of Operator**..............................

NOTE.—This order is good only for date and hours shown, new order must be issued each day.

CONTRACT FOR ELECTRIC SERVICE

*Date*________________19. _

Agreement entered into this______day of____________19__, between the . . . . . . **Company** hereinafter called the Company, and__________ _ __________ ____________hereinafter called the Consumer.

The Company agrees in consideration of the promises and agreements hereinafter contained and to be performed by the Consumer, to furnish electricity to the premises occupied by the Consumer at____________ ______ ____________for the operation of____________watt Incandescent Lamps, ________Arc Lamps,________H.P. Motors, provided that the electrical equipment of said premises shall be in condition satisfactory to the . . . . . . and to the Inspection Department of this Company. This contract shall be for the period of one year from the date hereof, and thereafter until the expiration of ten days' notice to discontinue, which notice shall be given in writing by either party.

Electric current to be charged for at the rate of________Pence per Kilowatt hour as measured by the Company's meter. All bills due the tenth of each month ; if paid on or before that date, a discount of 10 per cent will be allowed.

Minimum bill____per month.

The Consumer agrees to pay the cost of service connection.

The Company agrees to renew free of charge all burned out lamps not smaller than______watts nor larger than ______watts, when returned with bulbs unbroken, to the Company's office, . . . Street.

The Consumer agrees that the properly authorized agents of the Company shall, at all reasonable hours, have free access to the said premises, for the purpose of examining, repairing or removing meters, wires or other appliances, belonging to said Company.

The Consumer further agrees to provide space for and protect the meters wires and other appliances belonging to said Company, and hereby authorizes the Company to remove the meter and all other material belonging to them and cut off the supply of electric current whenever any bills for said service or supplies are in arrears, or upon violation of any of the terms or conditions of this contract.

While the Company will at all times endeavour to furnish a continuous supply of electricity to the Consumer at said premises, it does not guarantee such a supply, and shall not be liable for any damages which the Consumer may sustain by reason of the failure of the current.

It is understood and agreed that this contract shall apply to all additional incandescents, arcs, fans, or motors, that the Consumer shall cause to be connected, of which increased installation the Consumer shall notify the Company before its connection.

No promises, agreements. or representations of any canvasser or employee of the Company shall be binding upon the Company unless the same shall have been incorporated in this contract in writing before the same is signed and accepted.

Accepted. ____________________________

By________________________

Electric Department.

UNDERGROUND CABLE REPORT

Report for Month Ending ________________ 19___

	______19___	______19___	Increase.	Decrease.
Number of Underground Services Laid				
Length of L. T. Mains Laid				
,, ,, H. T. ,, ,,				
,, ,, Feeders ,,				
,, ,, Conduit ,,				
Number of Junction Boxes Set				
,, ,, Manholes Built				

	____ 19___	____ 19___
Average Number of Men on Fortnightly Payroll		
,, ,, ,, ,, Weekly ,,		
Total Number of Men Employed		

	______ 19___			______ 19___		
	Armoured.	Lead covered.	Total.	Armoured.	Lead covered.	Total.
Length Cable used for service						
,, ,, ,, ,, L. T. Mains						
,, ,, ,, ,, H. T. ,,						
,, ,, ,, ,, Feeders						
,, ,, ,, ,, ,,						
Total						

	______19___	______19___
Work done on the following SPECIAL WORK ORDERS:	% of Work Finished.	% of Work Finished.

OVERHEAD LINES REPORT

*Report for Month Ending*_______________19____

	_____19___	_____19___	Increase.	Decrease.
Number of Poles Set				
Number of Poles Taken Out				
Length of Secondary Mains Erected				
Length of . . . . Volt Mains ,,				
Length of . . . . Volt Mains				
Length of . . . . Volt Feeders ,,				
Average Number of Men on Fortnightly Payroll				
,, ,, ,, ,, ,, Weekly ,,				
Total Number of Men Employed				

Work finished or in progress on the following SPECIAL WORK ORDERS:

___________19___	_________19______	% of Work Finished.		% of Work Finished.	

CONNECTION DEPARTMENT REPORT

*Report for Month Ending*________________________________19__

		__________19__					__________19__						
		Connected.	Dis-connected.	Net.	**Total to Date.**	**Connected Load K. W.**	Connected.	Dis-connected.	Net.	**Total to Date.**	**Connected Load K. W.**	**Increase.**	**Decrease.**
Lighting	City												
,,	Suburbs												
	Total												
Small power	City												
,, ,	Suburbs												
	Total												
Arc Lights	City												
,, ,,	Suburbs												
	Total												

	______19__	______19__	Increase.	Decrease.
Average Number of Men on Fortnightly Payroll				
,, ,, ,, , ,, Weekly ,,				
,, ,, ,, , employed on Connections				
,, ,, , , ,, ,, ,, Repairs				
,, ,, ,, , ,, ,, ,, Inspection				
,, ,, ,, ,, ,, ,, ,, Changing System				
Total Number of Men Employed				
Average Number of Complaints attended to per day				
Total Number of Complaints received during Month				
Average Number of Connections made per day				
Average Number of Disconnections made per day				

METER REPORT

*Report for Month Ending*________________19__

P.P.=Polyphase. *S.P.*=Single Phase.	________19__					________19__					Increase.	Decrease.
	HIGH TENSION.		LOW TENSION.		TOTAL	HIGH TENSION.		LOW TENSION.		TOTAL		
	S. P.	P. P.	S. P.	P. P.		S. P.	P. P.	S. P.	P. P.			
Meters set												
Meters removed												
Net increase in Meters												
Total number Meters installed												
Meters revised and repaired												
Meters calibrated												
Meters changed												
Av. Number of meters set per day												
" " " " remvd. " "												

	________19__	________19__
Average Number of Men on Fortnightly Payroll		
" " " " " Weekly "		
" " " " Employed on Meter Setting		
" " " " " " " " Inspecting		
" " " " " " " " Reading		
" " " " " " " " Testing and Repairs		

METERS INSTALLED AND REMOVED.

MAKER.	________19__						________19__					
	New Meters Rec'd from Factory.		INSTALLED.		REMOVED.		New Meters Rec'd from Factory.		INSTALLED.		REMOVED.	
	S. P.	P. P.	S. P.	P. P.	S. P.	P. P.	S. P.	P. P.	S. P.	P. P.	S. P.	P. P.
TOTAL												

MOTOR AND TRANSFORMER REPORT

*Report for Month Ending*________________________19___

MOTORS.

	________19__ (Single Phase.)					________19__ (Polyphase.)					Increase.	Decrease.
	Connec- ted.	Discon- nected.	Net.	Total to Date.	Connected Load in **K.W.**	Connec- ted.	Discon- nected.	Net.	Total to Date.	Connected Load in **K.W.**		
LIGHTING DEPARTMENT. Small Motors.–City " " Suburbs												
TOTAL												
POWER DEPARTMENT. Large Motors.–City " " Suburbs												
TOTAL												
GRAND TOTAL												

	________19__ (Single Phase.)	________19__ (Polyphase.)
Number of Motors Sold " " " Rented during Month " " " " to Date " " " Repaired at Company's Repa r Shops		

TRANSFORMERS.

	____________19__ (Single Phase.)					____________19__ (Polyphase.)				
	In-stalled.	Re-moved.	Net.	Total to Date.	Capacity K.W.	In-stalled.	Re-moved.	Net.	Total to Date.	Capacity K.W.
Transformers in Underground Chambers										
Transformers on Underground System										
Transformers on Over-Head Lines.—City										
” ” ” ” Suburbs										
TOTAL										
Provisional Transformers set										
Booster Transformers ”										

TRANSFORMERS AND MOTORS.

	____________19__ (Single Phase.)	____________19__ (Polyphase.)
Average Number of Men on Fortnightly Payroll		
” ” ” ” ” Weekly ”		
” ” ” ” ” Inspections and Repairs		
” ” ” ” Employed Setting Transformers		
” ” ” ” ” ” Motors		
Total Number of Men Employed		

(Memo of most important power connections made to be given on back of form.)

PUBLIC LIGHTING REPORT

*Report for Month Ending*____________19__

	______19__					______19__						
	Connected.	Disconnected.	Net.	Total to Date.	Connected Load in K. W.	Connected.	Disconnected.	Net.	Total to Date.	Connected Load in K. W.	**Increase.**	**Decrease.**
Arc Lamps.												
. . . C. P.—City												
,, Suburbs												
TOTAL												
. . . C.P.—City												
,, Suburbs												
TOTAL												
Long Burning Arcs.—City												
,, ,, ,, Suburbs												
TOTAL												
Private Arc Lamps.—City												
,, ,, ,, Suburbs												
TOTAL												
Incandescent Lamps.												
. . . Watt.—City												
. . . ,, ,,												
. . . ,, ,,												
. . . Watt.—Suburbs												
. . . ,, ,,												
. . . ,, ,,												
TOTAL												

	______19__	______19__
Number of Arc Lamps Erected		
,, ,, ,, ,, Removed		
,, ,, ,, ,, Tested		
,, ,, Arc Lamps Circuits in service		
,, ,, Hours Burning		
,, ,, Hours Outage		
,, ,, Arc Lamps Changed and Replaced by New Ones		
,, ,, Arc Lamps Repaired in Repair Shops		
Price received for . . . C. P. Arc Lamps		
,, ,, ,, . . . C. P. ,, ,,		

	______19__	______19__
Fines		
Average Number of Men on Fortnightly Payroll		
,, ,, ,, ,, Weekly Payroll		
,, ,, ,, Trimmers		
,, ,, ,, Helpers		
,, ,, ,, Inspectors		
,, ,, ,, Repair-men		
,, ,, ,, Men in Workshops		
,, ,, ,, Station and Office		

APPENDIX

RULES AND REGULATIONS, ETC.

In this country, and in certain of the British Colonies, the use of electrical energy in premises, etc., is governed largely by the I.E.E. Rules, the Board of Trade Rules, and the Home Office Regulations. On the American continent somewhat similar electrical installations are governed by the Fire Underwriters' Rules, i.e. the National Electrical Code, which is revised every two years.

Under the Electric Lighting Acts (1882 and 1888), regulations for electrical installations were drawn up by the Board of Trade with the object of: (i) securing the safety of the public and property, and (ii) securing a proper and sufficient supply of electrical energy. These Rules are of great economic importance in relation to safety to life and property, protection of apparatus, control, power and pressure losses, standardization, etc.

The following Rules and Regulations are indispensable to all those concerned in the carrying out of electrical installations—

Wiring Rules of the Institution of Electrical Engineers.

Home Office Regulations governing the installation and use of electricity in factories and workshops.

Home Office Regulations governing the installation and use of electricity in mines.

Board of Trade Regulations governing the generation, distribution, and supply of electricity.

Board of Trade Tramway Regulations governing the authorizing of lines on public roads; for regulating the use of electrical power; for preventing fusion or injurious electrolytic action of or on gas or water pipes or other metallic pipes, structures or substances; and for minimizing, as far as is reasonably

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practicable, injurious interference with the electric wires, lines, and apparatus of parties other than the company, and the currents therein, whether such lines do or do not use the earth as a return.

Lloyd's Register of British and Foreign Shipping, giving rules for the use of electric light on board vessels.

British Engineering Standards Association's Specification and Reports. These publications are most instructive in addition to representing approved British standard practice. Reports published or in preparation cover all the principal classes of electrical equipment for industrial service.

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The following Technical Primers (Pitman, 2s. 6d. net) will be found valuable for further information on the subjects specified—

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